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Criticality Safety Evaluation for In Situ Grouting in the Subsurface Disposal Area

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August 2003

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

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ABSTRACT

The purpose of this document is to address the potential for a criticality in the Subsurface Disposal Area because of the proposed in situ grouting process. A criticality safety study was performed to address issues relating to postulated criticality scenarios in the Subsurface Disposal Area for Operable Unit 7-13/14 in the Radioactive Waste Management Complex at the Idaho National Engineering and Environmental Laboratory.

Based on the results of this study, a criticality resulting from the application of the in situ grouting process is not credible with the expected fissile masses and waste forms in the Subsurface Disposal Area.

The author would like to acknowledge what an important role the initial work, completed by Larry J. Slate, played in the development of this report. Mr. Slate completed the preliminary criticality safety evaluation, computational modeling, number density calculations, and other calculations used in support of the generic grout and paraffin found in this report. His initial work served as the basis for this evaluation.

EXECUTIVE SUMMARY

The Subsurface Disposal Area (SDA) is the portion of the Radioactive Waste Management Complex established in 1952 as a disposal site for solid, low-level radioactive waste. Transuranic waste was received from the Rocky Flats Plant and disposed of in the SDA from 1954 to 1970. This study examines criticality safety issues associated with the use of in situ grouting (ISG) as a means of immobilizing the buried transuranic waste in the SDA. Only ^{239}Pu was analyzed, since it is by far the most reactive and abundant fissile material reported to be disposed of.

Various configurations and grouting matrices were evaluated to determine if any criticality concerns arise in conjunction with treating the buried transuranic waste contained in the SDA with ISG.

The purpose of this document is to determine whether fissile material in the SDA poses a criticality hazard because of the application of the ISG process. Additionally, this evaluation assesses the proposed plans, in conjunction with the method of operation, to identify the necessity for criticality controls relating to ISG and to ensure that a criticality hazard is not likely under credible scenarios. This document is issued in support of the feasibility study/preliminary documented safety analysis.

As shown by the study, a postulated criticality in the SDA is dependent on known parameters that affect criticality. These parameters include the amount of fissile mass and moderator present, the geometry of the configuration, the presence of diluents or neutron absorbers, reflection surrounding the fissile systems, and the concentration or distribution of the fissile material in the waste. Most of these parameters would have to be optimized in some combination to achieve a critical system. As deviations from optimum conditions occur, the reactivity of the systems decreases dramatically.

The calculational models developed in this criticality safety evaluation are very conservative. Each of the models assumes fissile material to be distributed in an orderly, homogeneous manner at optimum concentrations within the buried waste. Most of these models are not realistic. The optimized assumptions cannot occur in actual waste configurations, but were constructed to show the effect of each factor. In reality, the waste is distributed in a more heterogeneous manner within the waste zone. The presence of localized pockets of adequate fissile material to postulate a critical configuration is assumed. Encountering localized pockets of pure fissile material not associated with some waste matrix is unlikely. Optimum geometrical configurations that are fully reflected by a tight-fitting reflector are assumed. Assuming optimum geometrical configurations is contrary to past excavation evidence that indicates degradation of the waste packages has occurred. This is also contrary to the actual waste forms and the way, in most instances, that waste packages were dumped into the SDA and mechanically compacted. The presence of other neutronic absorber or diluent material is ignored in the models. Ignoring the degradation of the package, and the nature of the waste in which the fissile material is for the most part associated with neutronic absorbers or diluent materials, is in itself very conservative. The necessity of these factors leads to the conclusion that a criticality is not credible in the SDA during the application of the ISG process.

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ACRONYMS

CSE	criticality safety evaluation
DOE	U.S. Department of Energy
INEEL	Idaho National Engineering and Environmental Laboratory
ISG	in situ grouting
MCNP	Monte Carlo N-Particle Transport Code
MCS	Mobile Containment Structure
OU	Operable Unit
RFP	Rocky Flats Plant
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area

Criticality Safety Evaluation for In Situ Grouting in the Subsurface Disposal Area

1. INTRODUCTION

This document presents the criticality safety evaluation (CSE) for in situ grouting (ISG) in the Subsurface Disposal Area (SDA) at the Idaho National Engineering and Environmental Laboratory (INEEL). The SDA is located within the Radioactive Waste Management Complex (RWMC). The SDA was used to dispose of radioactive waste material in underground pits, trenches, soil vault rows, and similar structures. The majority of waste buried in the SDA consists of by-products from the U.S. Department of Energy (DOE) Rocky Flats Plant (RFP) nuclear weapons program plutonium manufacturing process. The remaining waste is from INEEL onsite disposal and non-RFP offsite disposal.

The purpose of this document is to determine whether fissile material in the SDA poses a criticality hazard because of the ISG process application. Additionally, this evaluation assesses the proposed plans in conjunction with the method of operation to identify the necessity for criticality controls relating to ISG and to ensure that a criticality hazard is not likely under credible scenarios. This document is issued in support of the feasibility study/preliminary documented safety analysis.

2. PROCESS DESCRIPTION

The stabilization concept includes injection of various cementitious, mineralogical, or polymeric stabilization agents into the void space created from the buried waste and contaminated soil matrix. Upon solidification, the resultant waste form encapsulates the buried waste material within a dense matrix, isolating the waste from surface and groundwater infiltration. Figures 1 through 4 illustrate a general view of the grouting operation. The reader is encouraged to become familiar with *In-Situ Buried Waste Stabilization Technologies at the Idaho National Engineering and Environmental Laboratory* (Loomis 1998) for the details of the probing operation. The following sections describe the grouting operation in more detail and evaluate the criticality implications.

2.1 Waste Content

The precise content of SDA waste is not known with absolute certainty. Several studies have been completed to estimate the contents of the waste disposed of in the SDA (Thomas 1999 and Clements 1982). A study has been completed that maps the entire SDA and provides a graphical representation of the location of individual disposals and shipment contents. Waste shipment log sheets have been discovered from the RFP containing information such as the generator, amount of waste, and waste type. Generalizations can be made to determine the hazardous and radionuclide content of the waste; however, the exact fissile content of the waste will continue to be unknown. This is because of the uncertainty associated with the accuracy of the reviewed records and original packaging operations.

The RWMC assigns a content code to each waste container. These are based on the process used for the waste. "Sludges" make up the predominant mass and volume of the waste. There are three general process sludge type wastes: (1) inorganic (741-742), (2) organic (743-744), and (3) salt (745). The other waste is generally debris (concrete/asphalt), metal, and trash (combustibles). For criticality safety purposes, these content codes are grouped into eight waste matrices. A waste matrix can cover a range of materials. Table 1 lists the RWMC waste matrix designations and gives some examples of waste covered by each matrix.

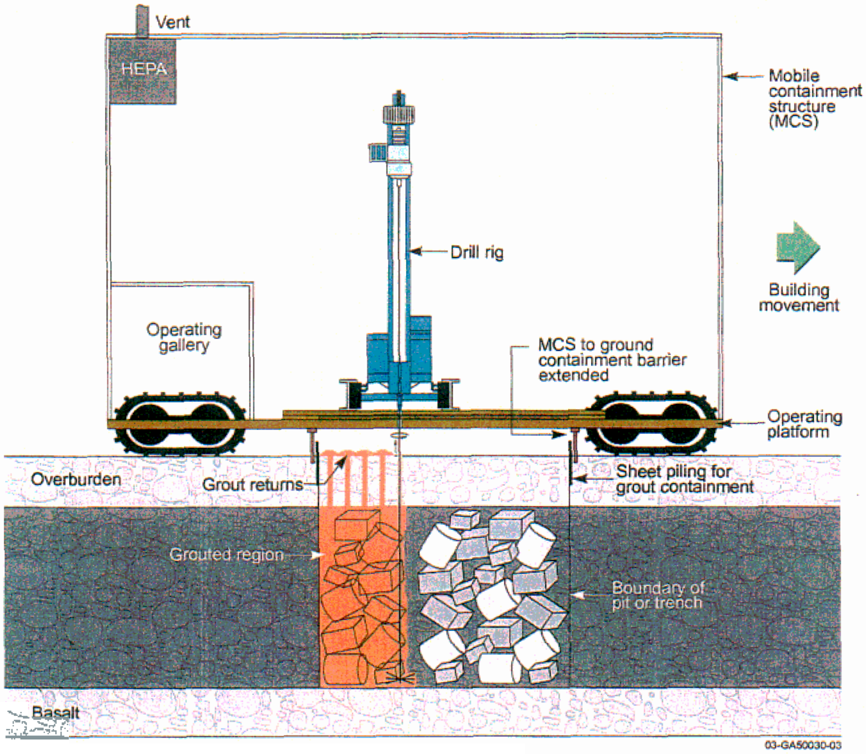

Figure 1. ISG delivery system in jet grouting mode.

Table 1. Listing of RWMC Waste Matrix Designations

General Classification	Waste Matrix	Examples of Typical Waste
Organic sludge	Oil and clay	Resins and combustibles
Combustible	Cellulose	Benelex, Plexiglas, cemented insulation and filter media
Debris	Brick	Fire brick—scarfed, coarse, pulverized
Debris, inorganic sludge	Concrete	Cemented and uncemented sludges
Salts	Salt	Evaporated, molten, Gibson, direct oxide reduction salts
Metal	Metal	Noncombustibles, noncompressibles, tantalum, lead
Debris	Glass/slag	Glass bottles, crucibles and molds, dirt, ceramic crucible

2.2 ISG Operations

The basic premise of ISG technology is to inject grout material into a selected subsurface area (waste pit) and produce a stable monolith. The monolith provides for both hot spot retrieval with enhanced contamination control, and encapsulation and stabilization of buried waste for in situ disposal. A series of beneficial bench-scale material studies and associated field-scale implementation tests have been performed. In 1997 the technology was successfully tested in the acid pit located within Operable Unit (OU) 7-13/14 (Waste Area Group 7). A complete description of the acid pit treatment is presented in the report associated with the Acid Pit Stabilization Project (Loomis et al. 1998). A general description of the ISG operation is discussed in the following subsections.

2.3 Treatment Technology Description

The major project facilities involved in the ISG process are the Mobile Containment Structure (MCS) and the grout supply facilities. Several MCS units may operate simultaneously in the SDA.

The MCS consists of a rigid, rectangular platform substructure and a flexible, steel-framed superstructure (see Figure 2). The outer dimensions of the substructure are approximately 45 × 42 ft with an 18-ft square opening through which the grouting operation takes place. The substructure consists of braced steel structural shapes and floor plate to provide rigidity. The steel framed superstructure is completely covered by polyester that is tensioned over the frame to provide a tight-fitting shell. Crane runway beams are integrated into the substructure on two sides of the opening. The height of each MCS unit will vary depending on the height of the drill rig mast the MCS encloses. Unit heights are expected to range from 30 to 45 ft.

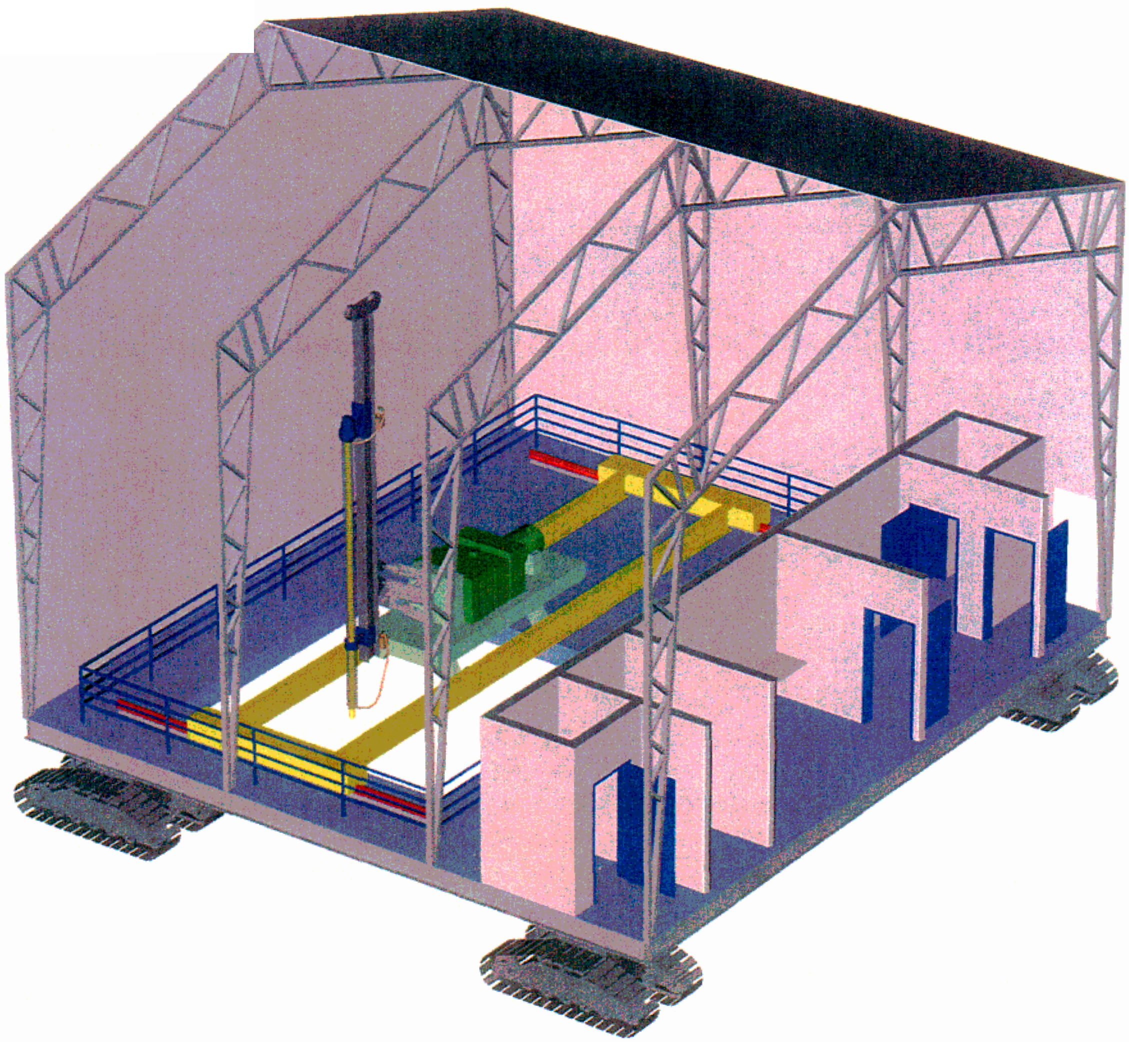

Figure 2. View of Mobile Containment Structure (MCS)

The drill rig (see Figure 3) is a roto-percussion type jet-grouting rig powered by an electric motor with electric over hydraulic remote controls. The rig is mounted on top of and moves with the trolley. The rig is capable of drilling through the soil waste matrix using a 3-9/16-in.-diameter rotating cone bit at a rate of 10 ft/min. The drill steel and bit are rotated as a single rigid unit by a hydraulic-powered drill motor. Simultaneous with the rotation, a hammering action is transmitted through the drill steel into the bit. The bit is driven through the soil/waste matrix until refusal (normally at basalt). No drill cuttings will be produced. Adding or removing drill steel is not anticipated during a drill/grouting cycle. The rig will be designed with a mast high enough for the drill steel to pass through the soil/waste matrix to basalt in a single stroke. Safety shields around the accessible connections for high-pressure hydraulic hoses and piping during operations are required, as recommended in lessons learned from previous drilling operations.

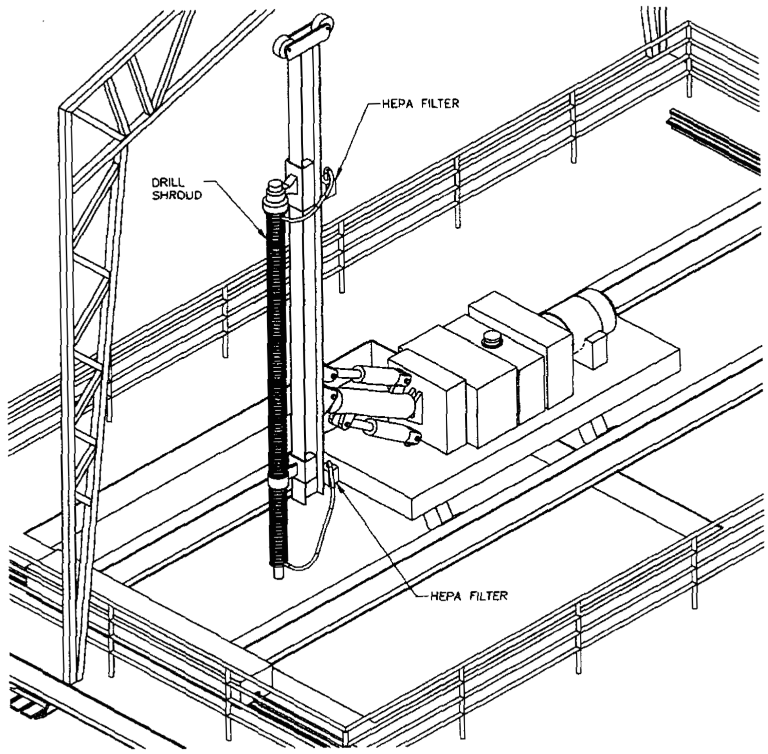

Figure 3. The ISG delivery system drill rig

Instrumentation providing graphical real time x, y, z positioning and jet-grouting parameters relative to the ground surface will be provided with the drill rig. These parameters include depth, penetration rate, thrust and circulation pressure, rotation torque, flows, and mast inclination. Other parameters relative to the grouting sequence include drill string rotational rate in rpm, step size, and dwell time on each step. The parameters will be recorded on a memory card and can be downloaded to any PC using software provided by the instrumentation vendor.

In the interest of safety, the drill rig will include: an automatic system relief valve, a remotely controlled bleed valve, a manually operated bleed valve, and an automatic pump clutch. Accessible high-pressure hoses and equipment will be shielded with safety shields during testing and maintenance operations.

The grouting facilities and equipment include:

- Silos
- Batch plant

- Delivery trucks
- Grout-receiving hopper
- Agitator
- High-pressure pump
- High-pressure flexible lines
- Drill stem
- Rotating cone bit.

The grouting system must be capable of injecting 30 gal/min into the soil matrix. The system will be designed for ease of cleaning grout injection nozzles using a water flush manifold in the glovebox.

The batch plant will be located outside of the SDA boundaries. Trucks will deliver the mixed grout from the batch plant to the grout-receiving hopper. The grout-receiving hopper, agitator, and grout pump will be located on a vehicle that will be adjacent to the MCS. When required, this vehicle will move with the MCS to each treatment area. Silos for storing dry components will be located alongside the batch plant. Dry components will feed into the batch plant colloidal mixer by screw conveyors. Water will be added to the mixer. When mixing is complete, the grout will be transferred into a holding tank and from the holding tank into the delivery trucks. Batch plant capacity will be approximately 7 yd^3/hr for each drill rig in operation. The grout-receiving hopper will feed into an agitator and into the grout pump through low-pressure lines. High-pressure flexible grout lines will lead from the grout pump to the drill rig mounted on the trolley and will feed grout to the drill stem and rotating cone bit. Flexible high-pressure lines within the MCS will be completely isolated from operators when pressurized. The cone bit injects the grout into the soil waste matrix as the drill stem is raised. The removable drill stem grouting nozzle subassembly will be replaced or cleaned in the glovebox using uncontaminated water.

2.4 Grouting Material

There are two types of grout that may be used for the subsurface grouting: cementitious and hydrocarbon-based grouts. Examples of cementitious grouts that have shown to be jet groutable in past INEEL demonstrations include Portland type1/2 mixed 1:1 water by mass, Portland type H mixed 1:1 water by mass, TECT HG, GMENT-12, and U.S. Grout. The only hydrocarbon-based grout that has been demonstrated is WAXFIX, which is primarily molten paraffin (120–140°F). In general, the cementitious grouts will require delivery of dry ingredients and mixing in the batch plant. The WAXFIX grout will be delivered in heated tanker trucks or trains in a molten form.

GMENT-12 is a cementitious grout that has a composition consisting of 90% Type 5 Portland Cement and Granulated Blast Furnace Slag, 9% silica fume, and 1% binder materials. The cured density of GMENT-12 is given as 1.84 g/cm^3 (Loomis 2002). Cured GEMNT-12 has a water content of approximately 10 wt%. The densities used to represent the GMENT-12 grout varied slightly from this number since it was calculated based upon water volume fractions of 10, 30, and 50%.

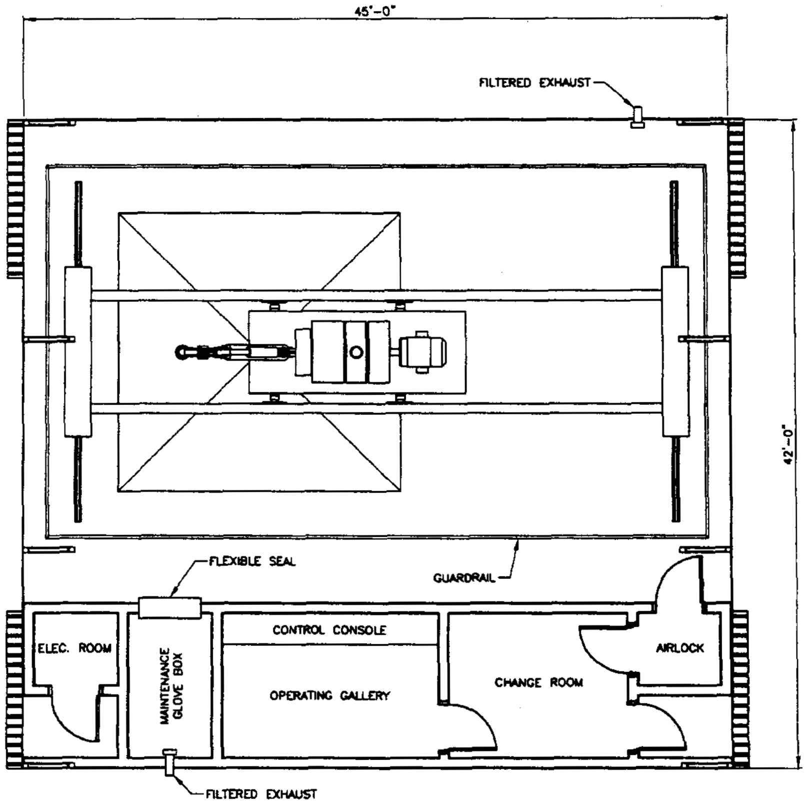

Figure 4. General Schematic of Grouting Operation (Top View).

TECT HG is a cementitious grout with a composition consisting of 30–40% Portland Cement, 30–40% Iron Oxide (FeO), 15–20% H_2O, and less than 5% of proprietary organic hydrocarbon compositions. The density of cured TECT HG is given as 2.16 g/cm^3 (Loomis 2002).

U.S. Grout is a cementitious grout that has a composition consisting of 50% Portland Cement and 50% Hess pumice. The density of cured U.S. Grout is given as 1.65 g/cm^3 (Loomis 2002).

The actual water weight percent for the various grouts ranged from approximately 50 wt% initially (at injection) to approximately 10 wt% for the cured grout.

The densities used to represent the grout varied slightly from these numbers since they were calculated based upon varied water volume fractions of 10, 30, and 50%. Analyzing this range of water volume fractions envelopes any variance in the composition of the grouts because of an increase or decrease in the amount of water present. The compositions of these mixtures can be found in Appendix A.

3. REQUIREMENTS DOCUMENTATION

No unique requirements are applicable to this evaluation. No limits are being developed within this evaluation. This evaluation is being performed to provide a basis of credibility for postulated criticality scenarios with the grouting process.

4. METHODOLOGY

Calculations were performed using the Monte Carlo N-Particle Transport Code (MCNP), version 4B2, computer code system (RSIC 1997). MCNP is a Monte Carlo transport code used to determine k_{eff} for systems containing fissionable material. The cross-section libraries used for this analysis contained the "point-wise" or "continuous-energy" cross sections, although MCNP can be used with multigroup cross sections also. The MCNP-4b code on the workstations is verified per company software quality assurance plans (Montierth 2000).

Because criticality limits are not being developed for implementation by this study, comprehensive validation work will not be addressed. Criticality in the SDA would require moderation; one can say that the moderated systems evaluated here have been well-validated by many critical experiments. Other experiments exist that could be used to validate calculations performed here.

The systems analyzed in this report consisted of plutonium dispersed in various waste matrices, including cementitious grout and paraffin. The geometry of the evaluated systems compromised waste materials and plutonium in a finite spherical form (optimized systems) and a rectangular form (slabs) of infinite extents in the horizontal directions. A set of cases evaluated finite GMENT-12 grout slabs. This was done to provide a reactivity comparison between the finite and infinite systems.

No critical experiments exist that exactly match the types of systems evaluated; however, modeling critical experiments that encompass the evaluated parameters adequately validates the various models. These parameters include material composition, moderation conditions, reflection conditions, and spectral neutron energy ranges.

Validation for these calculations requires experiments that consist of moderated plutonium systems and plutonium combined with silicon. Evaluated systems in this report had H/Pu ratios ranging from approximately 30 to 3,500.

A separate report was completed that evaluated critical plutonium/silicon configurations.[a] Experiments consisting of plutonium fuel rods (intermixed in a triangular lattice with silicon/dioxide rods) were performed in Obninsk, Russia in 1998 and 1999. A detailed description of the critical configurations can be found in Tsiboulia et al. (2000). A brief description of the experiments follows. Ten different rod types were used in the plutonium experiments. Each of the rods consisted of a stack of various discs or pellets of various materials. These materials included plutonium metal (canned in stainless steel), silica pellets, polyethylene pellets, stainless steel pellets, and boron carbide pellets. Each of the 10 different rods contained a combination of these pellets in a stacked configuration. The rods were then combined to create a critical system. The fuel tubes were arranged in a hexagonal array with a 5.1-cm pitch.

The experiments were modeled as described previously. Table 2 provides the calculated results for the experiments, using the ENDF/B-V cross section library. Table 2 also provides the H/Pu ratio and Si/Pu ratio for the experiments. The H/Pu ratio varied from 0 to 35, while the Si/Pu ratio varied from 23 to 42. The calculated neutron energy spectrum for these experiments indicates that the energy of the neutrons causing fission is primarily in the intermediate (0.625 eV to 100 keV) to fast (more than 100 keV) range. The average calculated k_{eff} for these experiments is 1.0070 ± 0.0003.

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a. This report, completed in 2002 by J.W. Nielsen, evaluated uranium and plutonium silicon dioxide experiments.

A set of evaluated cases consisting of PuO_2/polystyrene was reflected by plexiglass. The experiments were performed at Hanford between 1963 and 1970 and consisted of PuO_2/polystyrene cubes reflected by plexiglass plates. Twenty-nine experiments were performed with various configurations, concentrations of plutonium, and plutonium enrichments.

Table 2. Calculated results for the plutonium experiments.

Case Name	H/Pu	Si/Pu	$k_{eff} \pm \sigma$
BFS-81/1	0	23.4	1.0001 ± 0.0006
BFS-81/1A	0	23.4	0.9987 ± 0.0008
BFS-81/2	2.8	23.4	1.0055 ± 0.0008
BFS-81/3	5.6	23.4	1.0089 ± 0.0008
BFS-81/4	35.2	41.6	1.0178 ± 0.0008
BFS-81/5	35.2	41.6	1.0164 ± 0.0008
$Average: \ k_{avg} = \Sigma\,(k_i/\sigma_i^2)/\Sigma(1/\sigma_i^2),\ \sigma_{avg} = (1/\Sigma(1/\sigma_i^2))^{1/2}$ [a]			1.0070 ± 0.0003

a. (Bevington 1969)

The cubes were approximately 2 × 2 × 2 in. and were stacked on a split-table critical assembly. The two halves of the assembly were brought together and the neutron multiplication was determined using proportional counters. Some of the cubes were cut in the axial direction to allow flexibility in obtaining a critical height. The final critical configuration consisted of a rectangular block of PuO_2/polystyrene reflected on all six sides by plexiglass. The H/Pu ratios ranged from 5.87–65.4, with the C/Pu ratios varying 5.86–64.4. A more detailed description of these experiments can be found in an internal report (Nielsen 2003) that discusses validation of calculations containing HEU/graphite and Pu/polystyrene. The results from these cases can be found in Table 3.

Performance of this code package and computational platform is well-demonstrated for plutonium solution systems. Two cases were modeled that consisted of plutonium nitrate in a bare and reflected spherical configuration. A complete description of these cases can be found in Carter and Wilcox (1999).

The first case evaluated consisted of a 19.608-cm diameter radius spherical shell containing plutonium nitrate. The thickness of the 304-L stainless steel shell was 0.1219 cm. The spherical shell in this case was not reflected. The plutonium nitrate solution had a concentration of 39.0 g/L plutonium. The hydrogen to plutonium (H/Pu) ratio was approximately 700 for this case. The calculated $k_{eff} \pm 1\sigma$ for this case was 1.0134 ± 0.0013.

The second evaluated case consisted of the same spherical configuration, except this case was reflected by a 30-cm water reflector. The concentration of the plutonium nitrate was 25.2 g/L plutonium, with the sphere being full to a height of 18.754 cm above the centerline of the sphere. The H/Pu ratio was approximately 1,100. The calculated $k_{eff} \pm 1\sigma$ was 1.0154 ± 0.0010.

As shown by the results of these validation experiments, no bias caused by calculational methodology is warranted.

Table 3. Calculated results for the PuO2/polystyrene experiments.

Case Name	Description	H/Pu Ratio	$k_{eff} \pm \sigma$
Case 6	25.60 × 25.60 × 18.33-cm array of cubes	5.87	1.0170 ± 0.0009
Case 7	30.72 × 30.72 × 14.18-cm array of cubes	5.87	1.0177 ± 0.0008
Case 8	40.96 × 40.96 × 10.59-cm array of cubes	5.87	1.0173 ± 0.0007
Case 9	51.20 × 51.20 × 9.04-cm array of cubes	5.87	1.0193 ± 0.0008
Case 10	51.69 × 46.13 x 9.04-cm array of cubes	15.46	1.0285 ± 0.0010
Case 11	41.35 × 38.46 × 10.34-cm array of cubes	15.46	1.0270 ± 0.0010
Case 12	31.01 × 31.01 × 13.13-cm array of cubes	15.46	1.0247 ± 0.0010
Case 13	25.86 × 25.86 × 16.43-cm array of cubes	15.46	1.0233 ± 0.0009
Case 14	23.27 × 23.27 × 19.79-cm array of cubes	15.46	1.0275 ± 0.0010
Case 15	20.68 × 20.68 × 24.87-cm array of cubes	15.46	1.0256 ± 0.0009
Case 16	15.52 × 18.08 × 50.04-cm array of cubes	15.46	1.0214 ± 0.0010
Case 17	51.31 × 68.25 × 10.36-cm array of cubes	16.40	1.0045 ± 0.0009
Case 18	35.92 × 35.92 × 15.42-cm array of cubes	16.40	1.0088 ± 0.0008
Case 19	30.78 × 30.78 × 18.56-cm array of cubes	16.40	1.0051 ± 0.0007
Case 20	25.65 × 25.65 × 25.03-cm array of cubes	16.40	1.0056 ± 0.0008
Case 21	25.65 × 25.65 × 25.13-cm array of cubes	16.40	1.0072 ± 0.0009
Case 22	20.52 × 2052 × 49.15-cm array of cubes	16.40	1.0101 ± 0.0008
Case 23	61.08 × 61.08 × 16.35-cm array of cubes	65.37	1.0054 ± 0.0009
Case 24	50.90 × 61.08 × 17.48-cm array of cubes	65.37	1.0054 ± 0.0008
Case 25	50.90 × 50.90 × 18.68-cm array of cubes	65.37	1.0069 ± 0.0017
Case 26	50.90 × 45.81 × 19.69-cm array of cubes	65.37	1.0081 ± 0.0009
Case 27	40.72 × 45.81 × 22.06-cm array of cubes	65.37	1.0086 ± 0.0008
Case 28	40.72 × 40.72 × 23.58-cm array of cubes	65.37	1.0091 ± 0.0009
Case 29	40.72 × 30.54 × 29.64-cm array of cubes	65.37	1.0110 ± 0.0010
	Average : $k_{avg} = \Sigma\,(k_i / \sigma_i^2) / \Sigma(1/\sigma_i^2),\ \sigma_{avg} = (1/\Sigma(1/\sigma_i^2))^{1/2}$[a]		1.0138 ± 0.0002

a. (Bevington 1969)

5. DISCUSSION OF CONTINGENCIES

This evaluation provides a determination of credibility relating to a postulated criticality because of the application of the grouting process in the SDA. This report does not develop contingency analyses as normally thought of in the context of criticality safety. Specific criticality scenarios are not developed. No criticality limits or controls associated with the ISG process, as applied to the SDA, are being set in this evaluation. The contingency analysis is provided as a qualitative discussion that evaluates the conditions necessary to achieve a postulated critical condition. These conditions are then compared to the conditions that exist in the SDA.

An inadvertent criticality in the SDA caused by the ISG process is not credible. In order to create a critical configuration with reasonable quantities of fissile material, various factors must be met. An unsafe mass of fissile material must be present. This fissile mass must be concentrated, optimally moderated, and in a favorable or optimal geometrical configuration. The system needs near-full reflection and must be free from diluent- or neutron-absorbing materials.

The vast majority of the fissile material in the SDA is dispersed at relatively low concentrations. If an area of fissile material exists with a higher concentration, the various factors above would need to be near-optimal in order to achieve an unsafe condition. For example, approximately 10.2 kg of moist (1.5 wt% water) PuO_2 is required to create an unsafe condition. This system consists of uniform plutonium oxide powder in a small volume, which is free of diluent materials and fully reflected by an infinite perfect reflector. These idealistic conditions, however, do not exist in the SDA, nor will the application of the ISG process create them.

For cementitious and paraffin grouts, consideration has been given to all credible scenarios within the ISG treatability study that could have an impact on criticality safety. There are adequate margins of safety within the grouting operations to ensure that a criticality accident is not credible. The margin of safety includes the inability of sufficient plutonium to accumulate in a favorable geometry with necessary moderation, reflection, and minimal diluent. The margin of safety for this project is discussed in detail in the following section.

6. EVALUATION AND RESULTS

For criticality to occur in the SDA (because of the ISG process), several unlikely or highly unlikely concurrent parameters must exist: (a) there must be sufficient fissile mass, (b) the fissile mass must be at or near the optimum concentration, (c) the fissile mass must be in a near optimal geometry, (d) there must be optimal or near-optimal moderation, (e) near-optimal reflection must exist, and f) the fissile mass must be in a waste matrix that lacks diluent and neutronic absorber material.

Calculational models are developed within this evaluation to show the reactivity effects from the elemental compositions of the various grouts. These calculational models are very conservative in nature, since optimum homogeneous distribution in a fully reflected system is assumed. The fissile material is for the most part dispersed in the waste at low concentrations. There is a possibility that a localized area of higher fissile concentration does exist; however, the fissile material is most likely combined with or dispersed in a waste matrix in some form or fashion, not a large cache of pure plutonium oxide awaiting a moderating media. Additionally, it is not credible that the plutonium oxide would be arranged in an optimum geometry, optimally moderated, without the presence of some neutron absorbers and diluents.

This evaluation consists of two phases. The first phase evaluates various grout matrices to determine any criticality concerns associated with grouting to treat buried waste contained in the SDA. The second phase involved evaluating scenarios associated with the actual physical process of grouting and the possibility to create a critical system from these processes.

The grout matrices evaluated include (a) a generic cementitious grout, (b) GMENT-12, (c) TECT HG, (d) U.S. Grout, and e) paraffin. The introduction of grout into the waste zone will fill the void spaces within the waste matrices and eventually form a monolith within the waste zone. Although the fissile mass contained in the subsurface pit is unknown and cannot be accurately defined, grouting scenarios can be simulated to conservatively estimate the amount of fissile mass required for criticality. Once the amount of fissile mass to create criticality is estimated, engineering judgments can be made to determine if conditions exist within the SDA for a credible event.

The Pu concentrations corresponding to unsafe conditions for infinite slab configurations and finite spherical configurations were determined for each of the grout matrices and the paraffin matrix. The results of these models, with a description of the matrices, are provided in this report.

The second phase of the evaluation identified mechanisms that included concentration of fissile material because of compaction and grout injection. These scenarios were evaluated using qualitative methods.

This evaluation considers grouting operations performed upon waste in the SDA as currently configured. Any pretreatment options, such as in situ thermal desorption, might necessitate the development of additional scenarios that may be postulated during the grouting process.

6.1 Evaluation of Grouting Materials

Each of the proposed grouting matrices was evaluated to determine the minimum fissile concentration to achieve $k_{eff} + 2\sigma$ and $k_{\infty} + 2\sigma$ values that were less than or equal to 0.95 and 1.0. The k_{eff} values corresponded to finite systems, with the k_{∞} values corresponding to infinite systems. The moisture content of the grouts was varied to be 10, 30, and 50 wt%. The fissile component of the plutonium oxide was assumed to be 100% ^{239}Pu. The fissile material was assumed to be distributed in a homogeneous manner throughout the grouting material. This homogeneous distribution is conservative, as it provides a reactive configuration that can be readily moderated, and ignored other neutron absorbers or diluent materials.

The cementitious grouts (GMENT-12, TECT HG, and U.S. Grout) were evaluated containing 10, 30, and 50 wt% H_2O by composition in order to envelop the various expected ranges for the proposed grouting operations. The grout containing 50% H_2O corresponds to the initial grout mixture that will be injected into the waste zone. Grouts containing a higher percentage of water are much easier to pump and flow better. Previous work evaluated generic cementitious grout in finite models that consisted of both a 208- and 104-L sphere. The proposed actual grouting material that this report evaluates only considers the 208-L spherical configuration.

The plutonium concentration was varied in order to determine the concentration at which $k_{eff}+2\sigma$ (finite) and $k_\infty + 2\sigma$ (infinite) for the system is equal to 0.95 and 1.0. The results of the parameter study can be found in Appendix C. The concentrations corresponding to $k_{eff}+2\sigma$ and $k_\infty + 2\sigma$ were derived from the equations associated with the curves that were fit to the parameterized data. In these models, the volume occupied by the plutonium oxide (PuO_2) was conservatively ignored. An infinite and a finite model were developed for each of the corresponding water percentages. The finite model consisted of a 208-L (55 gal) sphere of grout and fissile material. The sphere was fully reflected by a 100-cm (39.4-in.)-thick layer of grout. The grout material used in the reflector corresponded to the same compositional makeup of the grout combined with the plutonium, except the plutonium was not included in the reflector.

A more detailed description of the cases, along with the associated results, is given in the following sections.

6.1.1 Evaluation of Generic Cementitious Grout

Neutron multiplication factor k_{eff} and k_∞ were calculated within the preliminary criticality safety evaluation (Slate 2000) for the generic cementitious grouting material to determine the minimum concentration of plutonium to obtain a k_{eff} and k_∞ of 1.00. The finite spheres were modeled with 24 in. of reflection by the grouting material, which represents a near-infinite reflective system. When the generic grout was evaluated, no specific grouts had been identified for use (Slate 2000). The generic grout results are incorporated from the previous preliminary criticality safety evaluation (Slate 2000) for completeness. Table 4 shows the composition of the generic cementitious grout, containing 10 wt% H_2O, that was evaluated (Slate 2000).

Table 5 represents the results from the infinite and finite generic grout models. The grout was evaluated containing 10, 30, and 50 wt% H_2O in order to envelop the various expected ranges for the proposed grouting operations. The generic grout containing 50% H_2O corresponds to the initial grout mixture that will be injected into the waste zone. Grouts containing a higher percentage of water are much easier to pump and flow better.

Table 4. Composition of Generic Grout - 10 wt% Water.

Material	Mass Fraction
H	0.0056
O	0.4956
Si	0.3135
Al	0.0456
Na	0.0171
Ca	0.0826
Fe	0.0122
K	0.0192
Mg	0.0024
S	0.0012

Table 5. Generic Grout Matrix Results.

Case #	Water Percent (wt %)	Pu Density (g/cm^3)	Finite Pu Mass (g)	H/Pu Ratio	$k_\infty \pm 1\sigma$
Generic Grout Matrix					
Infinite System					
Conc1	50	0.0063	—	3,092	0.9925 ± 0.0006
Conc	30	0.0052	—	2,850	0.9952 ± 0.0006
Conc2	10	0.0040	—	1,982	0.9923 ± 0.0008
					$k_{eff} \pm 1\sigma$
Spherical Finite Volume 208 Liters (55-gallons)					
Drum1	50	0.0097	2,020	2,008	1.0005 ± 0.0016
Drum	30	0.0100	2,080	1,527	1.0019 ± 0.0020
Drum2	10	0.0118	2,450	672	1.0039 ± 0.0024
Spherical Finite Volume 104 Liters (27.5 Gallons)					
Drum11	50	0.0121	1,260	1,610	1.0003 ± 0.0020
Drum0	30	0.0131	1,360	1,131	1.0041 ± 0.0032
Drum22	10	0.0212	2,200	374	1.0033 ± 0.0028

The plutonium concentration within the grout was varied in order to determine the minimum concentration at which k_{eff} and k_∞ for the system is approximately equivalent to 1.0. In these models the volume occupied by the plutonium oxide (PuO_2) was conservatively ignored. Ignoring the volume occupied by the PuO2 has a small effect on the overall reactivity of the system, since in most cases the volume of the PuO2 is a small percentage of the overall system volume. An infinite and a finite model were developed for each of the corresponding water percentages.

The results from Table 5 indicate that an infinite system with cured grout (10% moisture content) is the most reactive. This is because the low water concentration provides a media with a lack of parasitic absorption because of the presence of hydrogen and other neutronic absorbers. Additionally, silica provides a good scattering media for infinite systems since it also has a relatively low absorption cross section. Since neutrons cannot be lost to leakage, this increases the number of thermal neutrons present, thus reducing the concentration of uranium necessary to achieve a critical system. The most reactive finite volume is the moist grout (50% moisture content). This is because, for smaller systems, the presence of moderating material is necessary to effectively thermalize the neutrons prior to their escaping from the system. In addition, the results indicate that a smaller volume (104 L) requires less fissile mass for a critical system than a larger volume (55 gal or 208 L). The plutonium mass required for a criticality in the smaller volume (27.5 gal or 104 L) is 1,260 g. Also, the results show that the plutonium concentration increases as the volume decreases; this is because of neutron leakage. Parametric studies for the grout matrix infinite and finite systems can be found in Appendix C.

6.1.2 Evaluation of GMENT-12 Grout

The preliminary CSE evaluated a generic cementitious grout. Since the issuance of the preliminary CSE, specific grout mixtures have been slated for evaluation as possible candidate grouts to be used in the actual grouting process. One type of grout chosen as a candidate for investigation was GMENT-12. GMENT-12 is a cementitious grout with a composition consisting of 90% Type 5 Portland Cement and Granulated Blast Furnace Slag, 9% silica fume, and 1% binder materials. For the purposes of this evaluation, the 1% binder material was replaced with silica fume. The compositions of these mixtures can be found in Appendix A.

Table 6 provides the composition of the GMENT-12 grout evaluated. The mass fractions corresponding to the various water fractions are presented. The computer calculational results are given in Table 7. The calculations were generated to determine the mass of plutonium for the associated k_{eff} and k_∞.

As these results show, the concentrations associated with an unsafe infinite system are rather low. This is because of the higher scattering cross sections associated with grouts of this composition type (higher silica low moderation), and the conservative nature of the associated nonleakage probability. In order to provide the reader with a feel for the fissile masses necessary to achieve an unsafe condition associated with these low concentrations, finite models were developed. The finite models contained fissile concentrations corresponding to those determined to be unsafe for the infinite models. The results from these various models are given in Table 8.

Table 6. Composition of GMENT-12 Grout.

Material	Mass Fraction 10% H_2O	Mass Fraction 30% H_2O	Mass Fraction 50% H_2O
H	0.0112	0.0336	0.0559
O	0.4441	0.5414	0.6388
Si	0.1468	0.1113	0.0758
Al	0.0391	0.0309	0.0226
Mn	0.0033	0.0026	0.0019
Ca	0.3004	0.2368	0.1732
Fe	0.0100	0.0079	0.0058
K	0.0028	0.0022	0.0016
Mg	0.0356	0.0281	0.0205
S	0.0066	0.0052	0.0038
Total	1.0	1.0	1.0

Table 7. GMENT-12 Grout Matrix Results.

GMENT-12 Grout Matrix		
Water Percent (wt %)	Pu Density (g/cm^3)	H/Pu Ratio
	Infinite System ($k_\infty+2\sigma$ =1.0)	
50	0.0051	3,114
30	0.00414	2,514
10	0.00283	1,350
	Infinite System ($k_\infty+2\sigma$ =0.95)	
50	0.00462	3,438
30	0.00376	2,768

10	0.00256	1,493	

Water Percent (wt %)	Pu Density (g/ cm^3)	Finite Pu Mass (g)	H/Pu Rato
	Spherical Finite System (k_{eff}+2σ =1.0) Volume 208 L (55 gal)		
50	0.0096	1,997	1,654
30	0.0118	2,454	882
10	0.1115	23,192	34
	Spherical Finite System (k_{eff}+2σ =0.95) Volume 208 L (55 gal)		
50	0.0085	1,768	1,869
30	0.0101	2,093	982
10	0.0985	20,488	39

Table 8. GMENT-12 Grout – Low Concentration Finite System Results.

GMENT-12 Grout – Finite Systems 10 wt% H_2O (2.83 ^{239}Pu g/L) Results			
Dimension (ft × ft × ft)	Volume (L)	Mass of ^{239}Pu (kg)	$k_{eff} \pm 1\sigma$
10 × 10 × 10	28,316	80.1	0.9105 ± 0.0007
15 × 15 × 15	95,569	270.5	0.9535 ± 0.0006
20 × 20 × 20	226,534	641.1	0.9720 ± 0.0006
30 × 30 × 30	764,554	2,163.7	0.9865 ± 0.0005

As these results show, when applying the low concentrations from an infinite system to a finite system, rather large unbelievable fissile masses still yield subcritical systems. This demonstrates that the postulated unsafe conditions associated with these low concentrations for the infinite systems are very conservative and misleading. Either excessively large systems containing low homogeneous concentrations, or (as will be shown next) smaller systems of higher concentration, are necessary to postulate an unsafe condition.

The results from the finite spherical cases (208 L) show that for optimized systems with grout composed of 50% H_2O, the fissile mass necessary in a localized area to postulate an unsafe condition is in the range of about 2,000 g.

6.1.3 Evaluation of TECT HG Grout

Another type of grout chosen as a candidate for investigation was TECT HG. TECT HG is a cementitious grout that has a composition consisting of 30–40% Portland Cement, 30–40% Iron Oxide (FeO), 15–20% H_2O, and less than 5% of proprietary organic hydrocarbon compositions. For the purposes of this evaluation, the organic material was replaced with the other remaining compositions. The compositions of these mixtures can be found in Appendix A.

The TECT HG grout contains approximately 17% H_2O corresponding to the initial grout mixture that will be injected into the waste zone. The grout was evaluated at values higher than 17% in order to provide a basis for comparison between the grouts.

The composition of the TECT HG grout evaluated is given in Table 9. The mass fractions corresponding to the various water fractions are presented. Table 10 provides the results of the computer calculations. The calculations were generated to determine the mass of plutonium and the associated k_{eff}.

Table 9. Composition of TECT HG Grout.

Material	Mass Fraction 10% H_2O	Mass Fraction 30% H_2O	Mass Fraction 50% H_2O
H	0.0112	0.0336	0.0559
O	0.3578	0.4771	0.5965
Si	0.0513	0.0410	0.0308
Al	0.0124	0.0099	0.0074
Na	0.0005	0.0004	0.0003
Ca	0.2295	0.1836	0.1377
Fe	0.3230	0.2429	0.1627
K	0.0021	0.0017	0.0013
Mg	0.0067	0.0054	0.0040
S	0.0055	0.0044	0.0032
Total	1.0	1.0	1.0

As shown by these results, the fissile concentrations that equate to the postulated unsafe condition (in an infinite by infinite by infinite system) are greater than those corresponding to the GMENT-12 grout.

The finite cases show that for optimized systems the fissile mass necessary in a localized area to postulate an unsafe condition is in the range of about 2,300 g, corresponding to the case in which the grout is composed of 50% H_2O.

Table 10. TECT HG Grout Matrix Results.

TECT HG Grout Matrix		
Water Percent (wt %)	Pu Density (g/cm^3)	H/Pu Ratio
	Infinite System ($k_\infty+2\sigma=1.0$)	
50	0.00776	2,441
30	0.00839	1,658
10	0.00915	653
	Infinite System ($k_\infty+2\sigma=0.95$)	
50	0.00704	2,691
30	0.00760	1,830
10	0.00825	724

Water Percent (wt %)	Pu Density (g/cm^3)	Finite Pu Mass (g)	H/Pu Ratio
Spherical Finite System ($k_{eff}+2\sigma=1.0$) Volume 208 Liters (55 gallons)			

50	0.0123	2,558	1,540
30	0.0155	3,224	897
10	0.047	9,776	127
Spherical Finite System (k_{eff}+2σ =0.95) Volume 208 Liters (55 gallons)			
50	0.011	2,288	1,722
30	0.0136	2,829	1,023
10	0.032	6,656	187

6.1.4 Evaluation of U.S. Grout

Another type of grout chosen as a candidate for investigation was U.S. Grout, a cementitious grout with a composition consisting of 50% Portland Cement and 50% Hess pumice. The compositions of these mixtures can be found in Appendix A.

The composition of the U.S. Grout evaluated is given in Table 11. The mass fractions corresponding to the various water fractions are presented. Table 12 provides the results of the computer calculations. The calculations were generated to determine the mass of plutonium and the associated k_{eff}.

Table 11. Composition of Cementitious U.S. Grout.

Material	Mass Fraction 10% H_2O	Mass Fraction 30% H_2O	Mass Fraction 50% H_2O
H	0.0112	0.0336	0.0559
O	0.4731	0.5652	0.6575
Si	0.2105	0.1638	0.1170
Al	0.0470	0.0365	0.0261
Na	0.0079	0.0062	0.0044
Ca	0.2108	0.1640	0.1171
Fe	0.0157	0.0122	0.0087
K	0.0089	0.0070	0.0050
Mg	0.0094	0.0074	0.0053
S	0.0045	0.0036	0.0025
Ti	0.0007	0.0005	0.0004
Total	1.0	1.0	1.0

Table 12. U.S. Grout Matrix Results.

Cementitious U.S. Grout Matrix		
Water Percent (wt %)	Pu Density (g/cm^3)	H/Pu Ratio
Infinite System (k_∞+2σ =1.0)		
50	0.00572	3,116
30	0.00473	2,625
10	0.00342	1,441
Infinite System (k_∞+2σ =0.95)		
50	0.00519	3,435

30	0.00428	2,900
10	0.00309	1,595

Water Percent (wt %)	Pu Density (g/cm^3)	Finite Pu Mass (g)	H/Pu Ratio
Finite System (k_{eff}+2σ =1.0) Volume 208 Liters (55 gallons)			
50	0.0099	2,059	1,801
30	0.0113	2,350	1,103
10	0.025	5,200	197
Finite System (k_{eff}+2σ =0.95) Volume 208 Liters (55 gallons)			
50	0.00875	1,820	2,038
30	0.00974	2,026	1,275
10	0.019	3,952	259

As shown by these results, the fissile concentrations that equate to an unsafe condition in an infinite system are greater than those corresponding to the GMENT-12 grout.

The finite spherical cases show that for optimized systems the fissile mass necessary in a localized area to postulate an unsafe condition is in the range of about 2,000 g, wherein the grout is composed of 50% H_2O.

6.1.5 Summary of Cementitious Grout Cases

These grout systems evaluated are very conservative. A fully reflected optimum geometry (spherical) is assumed. The fissile material is homogeneously distributed throughout the grout with the absence of any other diluent- or neutronic-absorbing material. This will not be the case as the grout is injected into the waste zone materials. The grout will be injected by a high-pressure system and will fill the voids and gaps that currently exist in the waste zone. The force of injecting the grout will tend to randomly disperse the fissile material, thus creating a less reactive configuration, as opposed to homogeneously mixing the material in such an optimized fashion. Some localized concentration of fissile material could occur because of the injection grouting force, but it will not occur in the conservative configuration (optimum geometry, optimum moderation, no absorber or diluent material present, and fully reflected) needed to postulate the formation of a critical configuration. There is no mechanism from grouting that will preferentially concentrate the fissile material into such an optimized fashion.

6.1.6 Evaluation of Paraffin Grout

The last type of grout chosen as a candidate for investigation was paraffin. Paraffin is a hydrocarbon-based composition grout. Table 13 lists the composition of the paraffin grout ($C_{25}H_{52}$). The density of the paraffin grout is 0.93 g/cm^3.

Table 13. Composition of Paraffin Grout.

Material	Mass Fraction
C	0.8514
H	0.1486

Paraffin has many physical properties that make it a good choice as a grouting matrix material. The first is the ease in which paraffin can be pumped mechanically. The paraffin can be heated to an almost liquidlike state and can therefore be pumped easily into the waste zone. Unlike cementitious grouts, paraffin is very uniform in composition. It lacks the large particles present in the cementitious grouts that can physically damage and more readily wear upon the mechanical pumping systems. Paraffin will more effectively fill voids and gaps within the waste zone materials. The paraffin actually saturates and permeates some of the waste zone matrices before curing; thus providing a good matrix for the immobilization of radionuclides.

Neutron multiplication factor k_{eff} and k_{∞} were calculated within the preliminary criticality safety evaluation (Slate 2000) for the paraffin grouting material to determine the minimum concentration of plutonium to obtain a k_{eff} and k_{∞} of 1.00. The finite spheres were modeled with 24 in. of reflection by the grouting material. The 24 in. of reflection represents a near-infinite reflective system. Table 14 represents results from the infinite and finite paraffin matrix models.

The results given in Table 14 demonstrate the fissile masses needed to achieve an unsafe condition within a paraffin matrix; however, the concentration and fissile masses associated with an unsafe condition for the finite systems are based upon the material being distributed homogeneously over the entire 208-L spherical volume. Paraffin is very similar in chemical composition (CH_2) and density (0.92 g/cm^3) to polyethylene. For cases consisting of ^{239}Pu moderated optimally in fully reflected, full density polyethylene, critical systems can theoretically be achieved with fissile masses of about 380 g. These theoretical systems are much smaller in volume and have a higher concentration of fissile material, but are far from the actual configurations of the material in the SDA. The fissile material is dispersed in a more heterogeneous fashion within the various waste drums, or is closely associated with a waste matrix if dispersed in a homogenous fashion. An example of a more homogeneous distribution would be the fissile material associated with sludge. The fissile material is intermixed intimately with the sludge and all of its associated neutronic absorbers and diluents. This would significantly increase the fissile mass necessary in the sludge matrix to achieve an unsafe condition.

Table 14. Paraffin Matrix Results.

		Paraffin Matrix		
Case #		Pu Density (g/ cm^3)	H/Pu	$k_{\infty} \pm 2\sigma$
		Infinite System		
Paraffwo		0.0097	3,378	0.9998 ± 0.0006
Case #	Pu Density (g/ cm^3)	Finite Pu Mass (g)	H/Pu	$k_{eff} \pm 2\sigma$
		Finite Volume 208 Liters		
Drum3	0.01125	2,340	2,913	0.9976 ± 0.0012
		Finite Volume 104 Liters		
Drum33	0.0128	1,330	2,560	1.0005 ± 0.0016

The necessary fissile masses and geometrical configuration, the optimum moderation conditions without any neutronic absorbers, and present diluent material lead to the conclusion that the formation of a critical system, because of the use of paraffin grout within the SDA, is not credible.

6.2 Evaluation of Criticality Because of the Physical Processes of ISG

Process knowledge and archived shipping reports indicate that the waste containers are in various stages of deterioration. The integrity of the containers may range from completely disintegrated to structurally sound; therefore, the possibility of puncturing an overloaded drum and concentrating fissile material from the grouting operation does exist. The identified plutonium pathways, resulting in the accumulation of plutonium, are compacting the waste and injecting the grout into the subsurface. A detailed discussion of each identified pathway is discussed in the following subsections.

6.2.1 Compaction

As the drill stem is inserted into the waste environment, the potential for the waste to become locally compacted or consolidated increases. The consolidation of the fissile mass may result in a small increase in the reactivity of the waste; however, the small diameter of the drill stem will limit the compaction/consolidation of the waste. The accumulation of fissile material within the drill stem is not of concern because the drill stem is geometrically safe (9-cm diameter). In addition, grouting matrix will be released from the drill stem at a positive flow while the drill stem is inserted into the subsurface.

The force of injecting the grout will tend to disperse localized concentrations of fissile material, as opposed to preferentially mixing the fissile material homogeneously in an optimized configuration because of compaction. Some localized concentration of fissile material could occur from the force of the injection grouting, but it will not occur in the conservative configuration (optimum geometry, optimum moderation, no absorber or diluent material present, and fully reflected) needed to postulate the formation of a critical configuration. There is no mechanism because of grouting that will preferentially concentrate the fissile material into such an optimized fashion.

6.2.2 Injection

The grouting matrix is ejected from the drill stem nozzle at a pressure of 400 bars and produces a nominal radial mixing distance of grouting matrix and waste of 29 cm. The drill stem is withdrawn in 5-cm increments and grouting matrix is injected into the waste media for approximately 4–6 seconds. The total nominal effected mixing volume is 13.2 L. This volume equates to approximately 6% of a disposed drum; therefore, there is minimal potential for plutonium migration/consolidation from injecting the grout into the subsurface.

The force of injecting the grout will tend to disperse localized concentrations of fissile material randomly, as opposed to homogeneously mixing the material in such an optimized fashion. Some localized concentration of fissile material could occur from the force of the injection grouting, but it will not occur in the conservative configuration (optimum geometry, optimum moderation, no absorber or diluent material present, and fully reflected) needed to postulate the formation of a critical configuration. There is no mechanism due to grouting that will preferentially concentrate the fissile material into such an optimized fashion.

7. DESIGN FEATURES AND ADMINISTRATIVELY CONTROLLED LIMITS AND REQUIREMENTS

7.1 Grouting Operations

The following subsections identify necessary controls developed during this criticality safety evaluation for the in situ grouting operation.

7.2 Administrative Controls

No administrative controls associated with in situ grouting incorporating any of the evaluated grouting matrices have been identified. It should be mentioned that the addition of ^{10}B to any grouting system containing paraffin would add an additional margin of safety, and defense in depth, that would eliminate any postulated critical system involving 350 to 450 g of ^{239}Pu. This low fissile mass corresponds to the minimum critical mass for an idealized system.

7.3 Engineering Controls

No engineering controls associated with in situ grouting incorporating any of the evaluated grouting matrices have been identified.

8. SUMMARY AND CONCLUSIONS

This criticality evaluation assesses the criticality potential of in situ grouting in the SDA. These analyses evaluate the criticality potential of injecting grout matrices into the SDA. Based on the analyses presented in this criticality safety evaluation, there are no criticality hazards from injecting either cementitious grouting matrices or paraffin as a grout matrix within the SDA.

The results indicate that a large quantity of homogeneously mixed plutonium in the grouting matrix is required to create a criticality event. The grout moisture content was varied to represent the conditions that will be experienced within the SDA. The 50% moisture content represents the nominal moisture content at which the grout will be injected into the subsurface, the 30% moisture content represents an intermediate state, and the 10% moisture content represents a cured grout. The computer modeling results for the finite configurations indicate that the 50% moisture content is the most reactive. The required unsafe mass of plutonium for a finite volume (208 L) to postulate a criticality event is about 2,000 g of ^{239}Pu for the GMENT-12 grouting material, 2,500 g of ^{239}Pu for TECT HG grouting material, and 2,000 g of ^{239}Pu for the U.S. Grout material.

Scenarios were also calculated for the paraffin grouts (Slate 2000) that could be used to encapsulate the buried waste. The required unsafe plutonium mass for the paraffin grout for a finite volume (104 L) to postulate a criticality event is 1,330 g. Smaller unsafe fissile masses could be determined but require optimum conditions that will not occur in the SDA.

As the plutonium is dispersed homogeneously over the entire volume of the drum, the system becomes overmoderated. There is no mechanism to homogeneously distribute the plutonium throughout the volume of a drum in the optimized conditions. The grout is most likely going to fill the voids within the waste contained in a drum. As the volume of the system is decreased, the mass of plutonium necessary to achieve a critical system decreases. This is because of the system shifting from an overmoderated system to an optimally moderated system. For plutonium paraffin systems, the optimum H/Pu ratio occurs in the range of 500–700. At these optimum moderation points, it should be noted that much less plutonium would be necessary to achieve a critical system (about 350–400 g for paraffin). Achieving these optimally moderated systems because of the in situ grouting process is not credible.

The calculational models developed in this CSE are very conservative. Each of the models assumes fissile material to be distributed in an orderly, homogeneous manner at optimum concentrations within the buried waste. In reality, the waste is distributed in a more heterogeneous manner within the waste zone. The presence of localized pockets of adequate fissile material to postulate a critical configuration is assumed. Encountering localized pockets of pure fissile material not associated with some waste matrix is unlikely. Optimum geometrical configurations that are fully reflected by a tight-fitting reflector are assumed. Assuming optimum geometrical configurations is contrary to to the very nature of the waste and past excavation evidence that indicates degradation of the waste packages has occurred. This is also contrary to the way, in most instances, that waste packages were dumped into the SDA and mechanically compacted. The presence of other neutronic absorber or diluent material is ignored in the models. The degradation of the package, and the nature of the waste in which the fissile material is for the most part associated intimately with the waste matrices, indicates that ignoring the inclusion of neutronic absorbers or diluent materials is in itself very conservative. The necessity of these factors in combination to postulate a critical system lead to the conclusion that a criticality is not credible in the SDA because of the application of the ISG process.

The grouting matrices evaluated in this CSE were chosen as representative compositions for each of the various grout types. In most cases, the elemental compositions were given as a range between a maximum and a minimum. Slight variations to the elemental compositions of the actual grout matrices might provide slightly higher or lower concentrations and masses associated with the postulated critical configurations. These slight variances will not change the conclusions of this evaluation.

Additionally, it should be noted that this evaluation considered the grouting process as applied to current waste configurations that have not been pretreated. The application of the grouting process to waste that has been subjected to pretreatments, such as In Situ Thermal Desorption, would need further evaluation.

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Appendix A

Number Densities and Material Compositions

Appendix A

Number Densities and Material Compositions

Table A-1. Grout Atom Densities for Generic Grout.

Isotope or Element	Atoms/b-cm
Pu-239	2.4441-05
H	4.90088-02
O	3.6418-02
Si	4.7003-03
Al	7.1166-04
Na	3.1321-04
Ca	8.6781-04
Fe	9.1988-05
L	2.0678-04
Mg	4.580-05
S	1.5761-06

A plutonium concentration of 0.0097 was used to calculate the plutonium atom densities.

Table A-2. Paraffin Atom Densities.

Isotope or Element	Atoms/b-cm
Pu-239	2.8346-05
C	3.9699-02
H	8.2571-02

Table A-3. Material Composition for Portland Cement in GMENT-12.

Composition	Typical wt.% of Composition	Normalized Composition
SiO_2	25.0	25.23
Al_2O_3	3.4	3.43
Fe_2O_3	2.8	2.83
CaO	64.4	64.98
MgO	1.9	1.92
SO_3	1.6	1.61
Total	99.1	100.00

Table A-4. Material Composition for Blast Furnace Slag in GMENT-12.

Composition	Typical wt.% of Composition	Normalized Composition
SiO_2	37.0	36.92
Al_2O_3	14.0	13.97
CaO	34.0	33.93
MgO	12.0	11.97
S	0.9	0.9
FeO	0.5	0.5
MnO	1.0	1.0
P_2O_5	0.01	0.01
K_2O	0.8	0.8
Total	100.21	100.00

Table A-5. Material Composition for Silica Fume in GMENT-12.

Composition	Typical wt.% of Composition	Normalized Composition
SiO_2	100.0	100.0
Total	100.0	100.0

Table A-6. Material Composition for Portland Cement in TECT HG.

Composition	Typical wt.% of Composition	Normalized Composition
SiO_2	21.6	21.95
Al_2O_3	4.6	4.68
Fe_2O_3	3.4	3.46
CaO	63.2	64.23
MgO	2.2	2.24
SO_3	2.7	2.74
Na_2O_3	0.19	0.19
K_2O	0.5	0.51
Total	98.39	100.00

Table A-7. Material Composition for Portland Cement in U.S. Grout.

Composition	Typical wt.% of Composition	Normalized Composition
SiO_2	21.6	21.94
Al_2O_3	4.7	4.75
Fe_2O_3	3.6	3.64
CaO	63.6	64.31
MgO	2.9	2.93
SO_3	2.4	2.43
Total	98.9	100.00

Table A-8. Material Composition for Hess Pumice in U.S. Grout.

Composition	Typical wt.% of Composition	Normalized Composition
SiO_2	70.5	78.16
Al_2O_3	13.5	14.97
Ca	0.8	0.89
MgO	0.5	0.55
SO_3	0.1	0.11
FeO	0.1	0.11
Fe_2O_3	1.1	1.22
TiO	0.2	0.22
K	1.8	2.00
Na	1.6	1.77
Total	90.2	100.00

Table A-9. GMENT-12 Atom Densities (Atoms/bn-cm) No ^{239}Pu Included.

Isotope or Element	10 wt% H_2O	30 wt% H_2O	50 wt% H_2O
Si	4.5339E-03	3.1210E-03	1.9467E-03
Al	1.2580E-03	9.0021E-04	6.0279E-04
Fe	1.5602E-04	1.1164E-04	7.4757E-05
Ca	6.5009E-03	4.6519E-03	3.1150E-03
Mg	1.2703E-03	9.0903E-04	6.0870E-04
S	1.7755E-04	1.2705E-04	8.5074E-05
Mn	5.1846E-05	3.7100E-05	2.4843E-05
P	5.1821E-07	3.7082E-07	2.4831E-07
K	6.2471E-05	4.4703E-05	2.9934E-05
H	9.6274E-03	2.6220E-02	4.0011E-02
O	2.4068E-02	2.6641E-02	2.8780E-02

Table A-10. TECT HG Atom Densities (Atoms/bn-cm) No ^{239}Pu Included.

Isotope or Element	10 wt% H_2O	30 wt% H_2O	50 wt% H_2O
Si	2.4754E-03	1.5375E-03	9.4240E-04
Al	6.2130E-04	3.8590E-04	2.3654E-04
Fe	7.8371E-03	4.5749E-03	2.5050E-03
Ca	7.7602E-03	4.8200E-03	2.9544E-03
Mg	3.7585E-04	2.3345E-04	1.4309E-04
S	2.3220E-04	1.4423E-04	8.8404E-05
Na	2.7842E-05	1.7293E-05	1.0600E-05
K	7.3099E-05	4.5404E-05	2.7830E-05
H	1.5042E-02	3.5037E-02	4.7724E-02
O	3.0299E-02	3.1373E-02	3.2055E-02

Table A-11. U.S. Grout Atom Densities (Atoms/bn-cm) No ^{239}Pu Included

Isotope or Element	10 wt% H_2O	30 wt% H_2O	50 wt% H_2O
Si	8.3863E-03	5.4752E-03	3.3698E-03
Al	1.9470E-03	1.2712E-03	7.8235E-04
Fe	3.1414E-04	2.0509E-04	1.2623E-04
Ca	5.8839E-03	3.8415E-03	2.3643E-03
Mg	4.3545E-04	2.8430E-04	1.7497E-04
S	1.5954E-04	1.0416E-04	6.4106E-05
Na	3.8839E-04	2.5357E-04	1.5606E-04
Ti	1.7467E-05	1.1404E-05	7.0185E-06
K	2.5692E-04	1.6774E-04	1.0324E-04
H	1.2419E-02	3.1273E-02	4.4910E-02
O	3.3074E-02	3.3176E-02	3.3250E-02

Appendix B

MCNP Input Listings

Appendix B

MCNP Input Listings

B1. Generic Cementitious Grout - Infinite Model - 50 wt% Water

```
Conc1
ISG CSE Plutonium Concentration in Grout 50 wt% H2o
   1  10  -1.4048   1 -2 -3 4 -5 6    $ Pu Grout matrix
   2  0             (-1:2:3:-4:5:-6)  $ Outside World

   *1  pz 0
   *2  pz 100
   *3  px 50
   *4  px -50
   *5  py 50
   *6  py -50

mode n
imp:n 1 0
   m10     94239.55c 1.5874-5 1001.50c 4.9088-2 8016.50c 3.6418-2
         14000.50c 4.7003-3 13027.50c 7.1166-4 11023.50c 3.1321-4
         20000.50c 8.6781-4 26000.55c 9.1988-5 19000.50c 6.9495-4
         12000.50c 1.3974-4 16032.50c 5.2970-5
c
c
kcode 1000. 1.0 5 20
ksrc    10 10 10  20 20 20  30 30 30  40 40 40
       -10 -10 10  -20 -20 20  -30 -30 30  -40 -40 40
       10 10 30  20 20 30  30 30 30  40 40 30
       -10 -10 30  -20 -20 30  -30 -30 30  -40 -40 30
c      set time limit
c
ctme 9900
c
print
```

B2. Generic Cementitious Grout - Infinite Model - 10 wt% Water

```
Conc2
ISG CSE Plutonium Concentration in Grout 10 wt% H2o
   1  10  -2.0640  1 -2 -3 4 -5 6   $ Pu Grout matrix
   2  0            (-1:2:3:-4:5:-6)  $ Outside World

   *1  pz 0
   *2  pz 100
   *3  px 50
   *4  px -50
   *5  py 50
   *6  py -50

mode n
imp:n 1 0
   m10    94239.55c 1.0079-5 1001.50c 1.9975-2 8016.50c 4.1470-2
          14000.50c 1.2463-2 13027.50c 1.8869-3 11023.50c 8.3045-4
          20000.50c 2.3009-3 26000.55c 2.4390-4 19000.50c 5.4827-4
          12000.50c 1.1025-4 16032.50c 4.1790-5
c
c
kcode 1000. 1.0 15 400
ksrc   10 10 10  20 20 20  30 30 30  40 40 40
      -10 -10 10  -20 -20 20  -30 -30 30  -40 -40 40
      10 10 30  20 20 30  30 30 30  40 40 30
      -10 -10 30  -20 -20 30  -30 -30 30  -40 -40 30
c     set time limit
c
ctme 9900
c
print
```

B3. Generic Cementitious Grout - Finite Model - 10 wt% Water

```
Drum1
ISG CSE 208 liter sphere Plutonium in Grout reflected by grout
  1 10 -1.4082  -1             $ Pu Grout matrix
  2 0          2           $ Outside World
  3 20 -1.3985  -2 1           $ Grout Reflection

  1 s 0 0 0 36.8
  2 s 0 0 0 100

mode n
imp:n 1 0 1
  m10    94239.55c 2.4441-5 1001.50c 4.9088-2 8016.50c 3.6418-2
         14000.50c 4.7003-3 13027.50c 7.1166-4 11023.50c 3.1321-4
         20000.50c 8.6781-4 26000.55c 9.1988-5 19000.50c 2.0678-4
         12000.50c 4.1580-5 16032.50c 1.5761-5
  m20    1001.50c 4.9088-2 8016.50c 3.6418-2  14000.50c 4.7003-3
         13027.50c 7.1166-4 11023.50c 3.1321-4  20000.50c 8.6781-4
         26000.55c 9.1988-5 19000.50c 2.0678-4  12000.50c 4.1580-5
         16032.50c 1.5761-5
c
c
kcode 1000. 1.0 15 400
ksrc  0 0 0  0 0 10  0 0 20  0 0 30  10 0 10  10 0 20  10 0 30  20 0 10
      20 0 20  20 0 30  30 0 10  30 0 20  30 0 30  -10 0 10  -10 0 20
      -10 0 30  -20 0 10  -20 0 20  -20 0 30  -30 0 10  -30 0 20  -30 0 30
      0 0 -10  0 0 -20  0 0 -30  10 0 -10  10 0 -20  10 0 -30  20 0 -10
      20 0 -20  20 0 -30  30 0 -10  30 0 -20  30 0 -30
      -10 -10 30  -20 -20 30  -30 -30 30
c
c    set time limit
c
ctme 9900
c
print
```

B4. Paraffin Grout - Infinite Model

```
Paraffwo
ISG CSE Plutonium Concentration in Paraffin Boron
   1  10  -0.9397    1 -2 -3 4 -5 6   $ Pu Paraffin matrix
   2  0             (-1:2:3:-4:5:-6)  $ Outside World

   *1  pz 0
   *2  pz 100
   *3  px 50
   *4  px -50
   *5  py 50
   *6  py -50

mode n
imp:n 1 0
   m10    94239.55c 2.4441-5 12000.50c 3.9699-2 1001.50c 8.2571-2
c
c
kcode 1000. 1.0 15 400
ksrc    10 10 10  20 20 20  30 30 30  40 40 40
      -10 -10 10  -20 -20 20  -30 -30 30  -40 -40 40
      10 10 30  20 20 30  30 30 30  40 40 30
      -10 -10 30  -20 -20 30  -30 -30 30  -40 -40 30
c     set time limit
c
ctme 9900
c
print
```

B5. Paraffin Grout - Finite Model

Drum3

```
ISG CSE 208 liter sphere Plutonium in Paraffin reflected by Paraffin
  1  10  -0.9413  -1           $ Pu Paraffin matrix
  2  0            2            $ Outside World
  3  20  -0.93   -2 1          $ Paraffin Reflection

  1  s  0 0 0 36.8
  2  s  0 0 0 100

mode n
imp:n 1 0 1
  m10    94239.55c 2.8346-5  6000.50c 3.9699-2  1001.50c 8.2571-2
  m20    6000.50c 3.9699-2  1001.50c 8.2571-2
c
c
kcode 1000. 1.0 15 400
ksrc   0 0 0  0 0 10  0 0 20  0 0 30  10 0 10  10 0 20  10 0 30  20 0 10
     20 0 20  20 0 30  30 0 10  30 0 20  30 0 30  -10 0 10  -10 0 20
     -10 0 30  -20 0 10  -20 0 20  -20 0 30  -30 0 10  -30 0 20  -30 0 30
     0 0 -10  0 0 -20  0 0 -30  10 0 -10  10 0 -20  10 0 -30  20 0 -10
     20 0 -20  20 0 -30  30 0 -10  30 0 -20  30 0 -30
     -10 -10 30  -20 -20 30  -30 -30 30
c
c     set time limit
c
ctme 9900
c
print
```

B6. Example MCNP Listing for GMENT-12 Grout - Infinite Model

```
Case GMENT12-1a13  ISG CSE Plutonium Concentration Varied in GMENT-12
c 10 wt% H2O
c 42.5 wt% Blast Furnace Slag
c 42.5 wt% Portland Cement
c 5 wt% Silica Fume
c 13.0 g/L 239Pu in Mixture
c Infinte x Infinite x Infinite Model
c
   1  10  4.7805-02    1 -2 -3 4 -5 6    $ Pu-H2O-GMENT12 Mixture
   2  0               (-1:2:3:-4:5:-6)  $ Outside World

   *1  pz 0
   *2  pz 100
   *3  px 50
   *4  px -50
   *5  py 50
   *6  py -50

mode n
imp:n 1 0
   m10     94239.55c 3.2749-5  1001.50c 9.6274-3  8016.50c 2.4134-2
         14000.50c 4.5339-3 13027.50c 1.2580-3
         20000.50c 6.5009-3 26000.55c 1.5602-4 19000.50c 6.2471-5
         12000.50c 1.2703-4 16032.50c 1.7755-4 15031.50c 5.1821-7
         25055.50c 5.1846-5
c
c
kcode 1000. 1.0 15 400
ksrc    10 10 10  20 20 20  30 30 30  40 40 40
      -10 -10 10  -20 -20 20  -30 -30 30  -40 -40 40
      10 10 30  20 20 30  30 30 30  40 40 30
      -10 -10 30  -20 -20 30  -30 -30 30  -40 -40 30
c    set time limit
c
ctme 9900
c
print
```

B7. Example MCNP Listing for GMENT-12 Grout – Finite 208L Model

```
Case GMENT12-3a-fin10 ISG CSE Plutonium Concentration Varied in GMENT-12
c 208 L of Grout (55 gallons) mixed with Pu239
c Reflected by grout of similar composition w/o Pu239
c 50 wt% H2O
c 24.5 wt% Blast Furnace Slag
c 24.5 wt% Portland Cement
c  1 wt% Silica Fume
c 10.0 g/L 239Pu in Mixture
c Spherical Model
1  10  7.5355-02   -1     $ Pu Grout matrix
2  20  7.5279-02   +1 -2  $ Grout Reflector
3  0               +2     $ Outside World

1  so   37.76
2  so  187.76

mode n
imp:n 1 1 0
c
c Pu in Grout
   m10    94239.55c 2.5191-5  1001.50c 4.0011-2  8016.50c 2.8830-2
         14000.50c 1.9467-3 13027.50c 6.0279-4
         20000.50c 3.1150-3 26000.55c 7.4757-5 19000.50c 2.9934-5
         12000.50c 6.0870-4 16032.50c 8.5074-5 15031.50c 1.9864-5
         25055.50c 2.4831-7
c
c Grout
   m20     1001.50c 4.0011-2  8016.50c 2.8785-2
         14000.50c 1.9467-3 13027.50c 6.0279-4
         20000.50c 3.1150-3 26000.55c 7.4757-5 19000.50c 2.9934-5
         12000.50c 6.0870-4 16032.50c 8.5074-5 15031.50c 1.9864-5
         25055.50c 2.4831-7
c
kcode 1000. 1.0 15 400
ksrc  0 0 0
c     set time limit
c
ctme 9900
c
print
```

B8. Example MCNP Listing for TECT HG Grout - Infinite Model

```
Case US_Grout-1a4  ISG CSE Plutonium Concentration Varied in US Grout
c 10 wt% H2O
c 45 wt% Hess Pumice
c 45 wt% Portland Cement
c 4.0 g/L 239Pu in Mixture
c Infinite x Infinite x Infinite Model
c
   1  10  4.7999-02    1 -2 -3 4 -5 6    $ Pu-H2O-US Grout Mixture
   2  0                (-1:2:3:-4:5:-6)  $ Outside World

   *1  pz 0
   *2  pz 100
   *3  px 50
   *4  px -50
   *5  py 50
   *6  py -50

mode n
imp:n 1 0
   m10    94239.55c 1.0076-5  1001.50c 1.2419-2  8016.50c 1.7781-2
          14000.50c 8.3863-3 13027.50c 1.9470-3
          20000.50c 5.8839-3 26000.55c 3.1414-4 19000.50c 2.5692-4
          12000.50c 4.3545-4 16032.50c 1.5954-4 15031.50c 5.1821-7
          11023.50c 3.8839-4 22000.50c 1.7467-5
c
c
kcode 1000. 1.0 15 400
ksrc    10 10 10  20 20 20  30 30 30  40 40 40
       -10 -10 10  -20 -20 20  -30 -30 30  -40 -40 40
       10 10 30  20 20 30  30 30 30  40 40 30
       -10 -10 30  -20 -20 30  -30 -30 30  -40 -40 30
c     set time limit
c
ctme 9900
c
print
```

B9. Example MCNP Listing for TECT HG Grout - Finite 208L Model

```
Case TectHG-2a-fin3  ISG CSE Plutonium Concentration Varied in TectHG
c 208 L of Grout (55 gallons) mixed with Pu239
c Reflected by grout of similar composition w/o Pu239
c 30 wt% H2O
c 30 wt% FeO
c 40 wt% Portland Cement
c 20.0 g/L 239Pu in Mixture
c Spherical Model
1  10  8.6838-02   -1    $ Pu Grout matrix
2  20  8.6687-02  +1 -2  $ Grout Reflector
3  0              +2     $ Outside World

1  so   37.76
2  so  187.76

mode n
imp:n 1 1 0
c
c Pu in Grout
   m10    94239.55c 5.0382-5  1001.50c 4.7724-2  8016.50c 3.2156-2
          14000.50c 9.4240-4 13027.50c 2.3654-4 11023.50c 1.0600-5
          20000.50c 2.9544-3 26000.55c 2.5050-3 19000.50c 2.7830-5
          12000.50c 1.4309-4 16032.50c 8.8404-5
c
c Grout
   m20    1001.50c 4.7724-2  8016.50c 3.2055-2
          14000.50c 9.4240-4 13027.50c 2.3654-4 11023.50c 1.0600-5
          20000.50c 2.9544-3 26000.55c 2.5050-3 19000.50c 2.7830-5
          12000.50c 1.4309-4 16032.50c 8.8404-5
c
c
kcode 1000. 1.0 15 400
ksrc   0 0 0
c     set time limit
c
ctme 9900
c
print
```

B10. Example MCNP Listing for US Grout - Infinite Model

```
Case US_Grout-1a4  ISG CSE Plutonium Concentration Varied in US Grout
c 10 wt% H2O
c 45 wt% Hess Pumice
c 45 wt% Portland Cement
c 4.0 g/L 239Pu in Mixture
c Infinite x Infinite x Infinite Model
c
  1  10  4.7999-02   1 -2 -3 4 -5 6   $ Pu-H2O-US Grout Mixture
  2  0              (-1:2:3:-4:5:-6)  $ Outside World

  *1  pz 0
  *2  pz 100
  *3  px 50
  *4  px -50
  *5  py 50
  *6  py -50

mode n
imp:n 1 0
  m10    94239.55c 1.0076-5  1001.50c 1.2419-2  8016.50c 1.7781-2
         14000.50c 8.3863-3 13027.50c 1.9470-3
         20000.50c 5.8839-3 26000.55c 3.1414-4 19000.50c 2.5692-4
         12000.50c 4.3545-4 16032.50c 1.5954-4 15031.50c 5.1821-7
         11023.50c 3.8839-4 22000.50c 1.7467-5
c
c
kcode 1000. 1.0 15 400
ksrc   10 10 10  20 20 20  30 30 30  40 40 40
      -10 -10 10  -20 -20 20  -30 -30 30  -40 -40 40
      10 10 30  20 20 30  30 30 30  40 40 30
      -10 -10 30  -20 -20 30  -30 -30 30  -40 -40 30
c     set time limit
c
ctme 9900
c
print
```

B11. Example MCNP Listing for US Grout - Finite Model

```
Case US_Grout-3a8  ISG CSE Plutonium Concentration Varied in US Grout
c 208 L of Grout (55 gallons) mixed with Pu239
c Reflected by grout of similar composition w/o Pu239
c 50 wt% H2O
c 25 wt% Hess Pumice
c 25 wt% Portland Cement
c 8.0 g/L 239Pu in Mixture
c Spherical Model
1  10  7.9215-02   -1    $ Pu-Grout-H2O matrix
2  20  7.9155-02  +1 -2  $ US Grout Reflector
3  0              +2     $ Outside World

1  so  37.76
2  so  187.76

mode n
imp:n 1 1 0
c
c Pu in US Grout
   m10    94239.55c 2.0153-5  1001.50c 4.4910-2  8016.50c 2.7137-2
          14000.50c 3.3698-3 13027.50c 7.8235-4
          20000.50c 2.3643-3 26000.55c 1.2623-4 19000.50c 1.0324-4
          12000.50c 1.7497-4 16032.50c 6.4106-5 15031.50c 5.1821-7
          11023.50c 1.5606-4 22000.50c 7.0185-6
c
c US Grout - no Pu - Reflector
   m20     1001.50c 4.4910-2  8016.50c 2.7097-2
          14000.50c 3.3698-3 13027.50c 7.8235-4
          20000.50c 2.3643-3 26000.55c 1.2623-4 19000.50c 1.0324-4
          12000.50c 1.7497-4 16032.50c 6.4106-5 15031.50c 5.1821-7
          11023.50c 1.5606-4 22000.50c 7.0185-6
c
kcode 1000. 1.0 15 400
ksrc   0 0 0
c
c    set time limit
c
ctme 9900
c
print
```

Appendix C

Parametric Study Results and Graphs

Appendix C

Parametric Study Results and Graphs

Table C-1. Infinite Grout Parametric Study.

Pu Concentration in Grout (g/cc)		$k_\infty \pm \sigma$
	50% Moisture Content	
0.0083		1.1332 ± 0.0004
0.0073		1.0676 ± 0.0004
0.0063		0.9925 ± 0.0003
0.0053		0.9035 ± 0.0004
0.0043		0.7985 ± 0.0003
	30% Moisture Content	
0.0072		1.1609 ± 0.004
0.0062		1.0849 ± 0.004
0.0052		0.9952 ± 0.0003
0.0042		0.8855 ± 0.0003
0.0032		0.7510 ± 0.0003
	10% Moisture Content	
0.006		1.2109 ± 0.0004
0.005		1.1213 ± 0.0004
0.004		1.0041 ± 0.0004
0.003		0.8626 ± 0.0004
0.002		0.6691 ± 0.0003

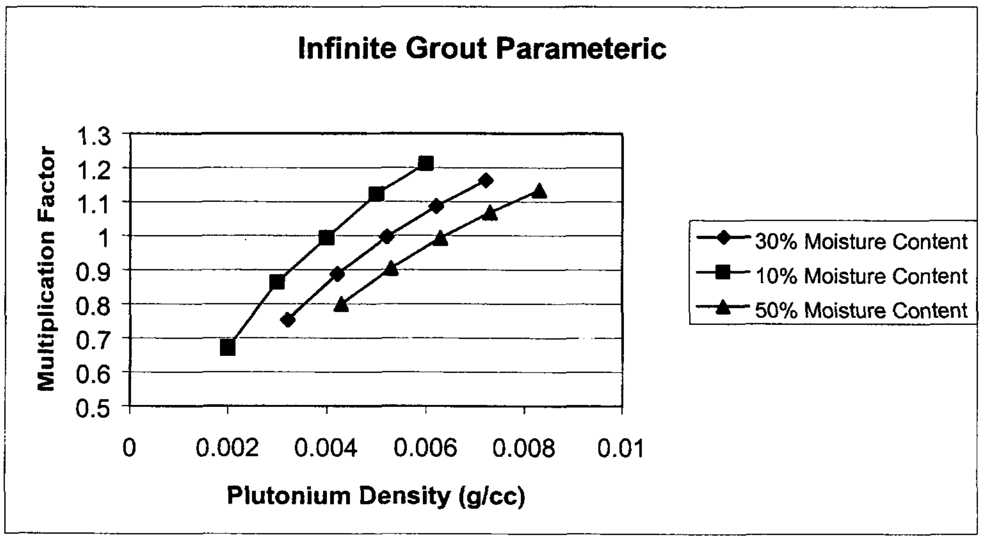

Figure C-1. Infinite Grout Parametric Study.

Table C-2. Finite (208 L) Grout Parameter Study.

Pu Concentration in Grout (g/cc)	$k_{eff} \pm \sigma$
50% Moisture Content	
0.0117	1.0779 ± 0.0009
0.0107	1.0437 ± 0.0009
0.0097	1.0005 ± 0.0009
0.0087	0.9535 ± 0.0008
0.0077	0.9014 ± 0.0008
30% Moisture Content	
0.0117	1.0751 ± 0.0010
0.0107	1.0409 ± 0.0010
0.0097	1.0019 ± 0.0010
0.0087	0.9574 ± 0.0010
0.0077	0.9075 ± 0.0012
10% Moisture Content	
0.0138	1.0480 ± 0.0013
0.128	1.0275 ± 0.0012
0.118	1.0039 ± 0.0012
0.0108	0.9746 ± 0.0011
0.0098	0.9437 ± 0.0012

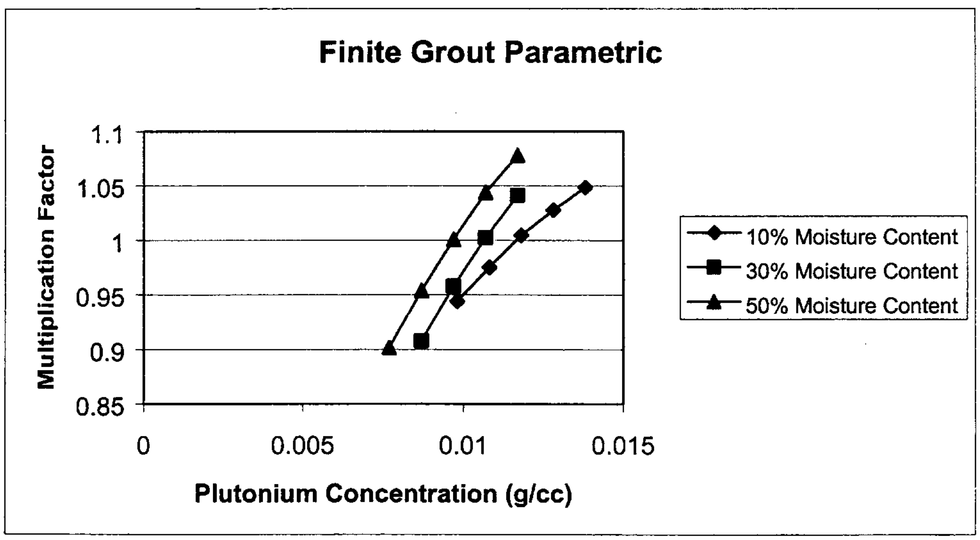

Figure C-2. Finite (208 L) Grout Parametric Study.

Table C-3. Finite (104 L) Grout Parametric Study.

Pu Concentration in Grout (g/cc)	$k_{eff} \pm \sigma$
50% Moisture Content	
0.0141	1.0579 ± 0.0010
0.0131	1.0273 ± 0.0011
0.0121	1.0003 ± 0.0010
0.0111	0.9641 ± 0.0010
0.0101	0.9281 ± 0.0009
30% Moisture Content	
0.0151	1.0521 ± 0.0011
0.0141	1.0305 ± 0.0011
0.0131	1.0041 ± 0.0016
0.0121	0.9773 ± 0.0011
0.0111	0.9448 ± 0.0011
10% Moisture Content	
0.0232	1.0206 ± 0.0013
0.0222	1.0135 ± 0.0013
0.0212	1.0033 ± 0.0014
0.0202	0.9964 ± 0.0013
0.0192	0.9843 ± 0.0013

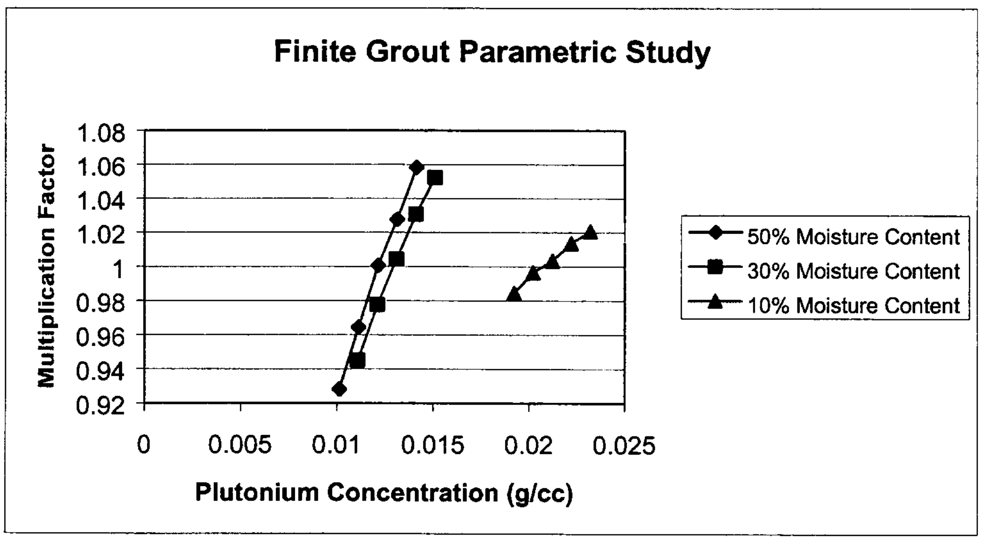

Figure C-3. Finite (104 L) Grout Parametric Study.

Table C-4. Infinite Paraffin Parametric Study.

Pu Concentration in Grout (g/cc)	$k_\infty \pm \sigma$
Paraffin Matrix	
0.0117	1.0971 ± 0.0003
0.0107	1.0509 ± 0.0003
0.0097	0.9998 ± 0.0003
0.0087	0.9430 ± 0.0003
0.0077	0.8811 ± 0.0003

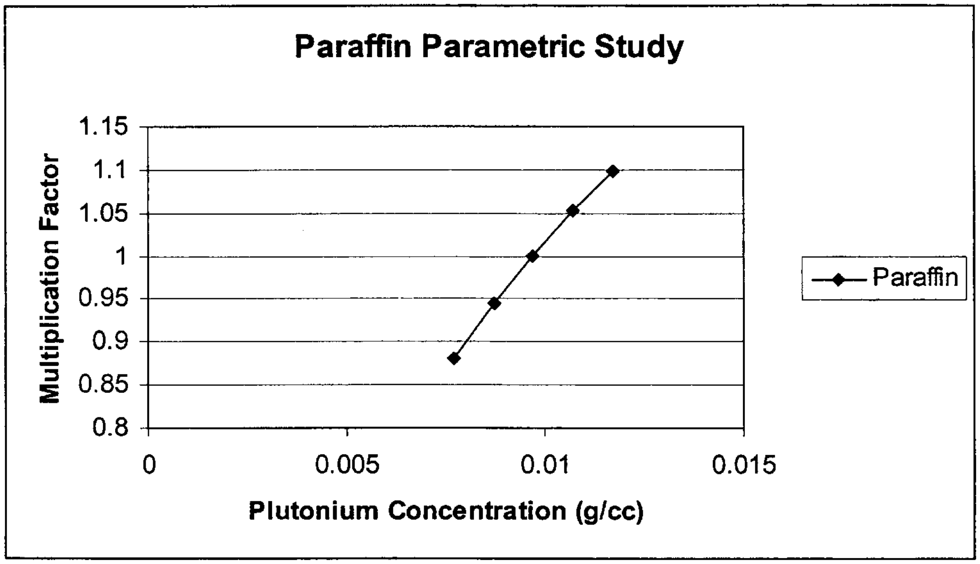

Figure C-4. Infinite Paraffin Parametric Study.

Table C-5. Finite (208 L)Paraffin Parametric Study.

Pu Concentration in Grout (g/cc)	$k_{eff} \pm \sigma$
Paraffin Matrix	
0.01325	1.00719 ± 0.0007
0.01225	1.0355 ± 0.0007
0.01125	0.9976 ± 0.0006
0.01025	0.9525 ± 0.0007
0.00925	0.9025 ± 0.0007

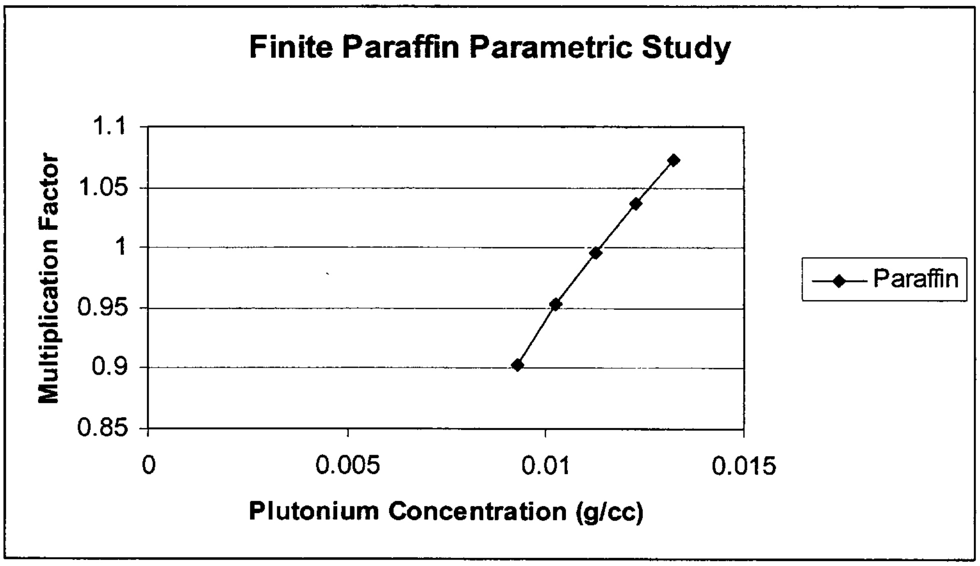

Figure C-5. Finite (208 L) Paraffin Parametric Study.

Table C-6. Finite (104 L) Paraffin Parametric Study.

Pu Concentration in Grout (g/cc)	$k_{eff} \pm \sigma$
Paraffin Matrix	
0.0148	1.00648 ± 0.0008
0.0138	1.0334 ± 0.0008
0.0128	1.0005 ± 0.0008
0.0118	0.9635 ± 0.0008
0.0108	0.9213 ± 0.0007

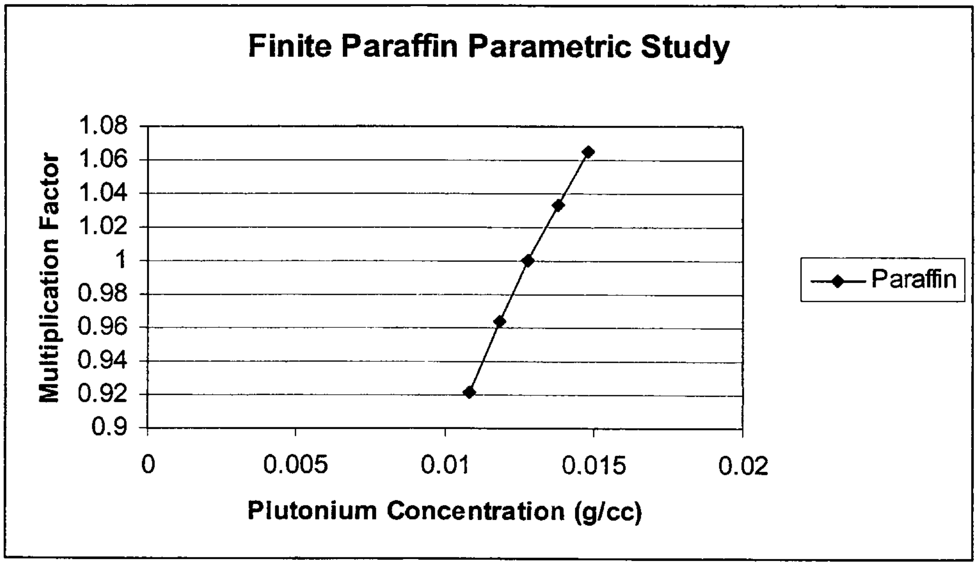

Figure C-6. Finite (104 L) Paraffin Parametric Study.

Table C-7. Infinite GMENT-12 Grout Parametric Study.

Pu Concentration in Grout (g/cc)		$k_\infty \pm \sigma$
	50% Moisture Content	
0.001		0.3201 ± 0.0002
0.002		0.5549 ± 0.0002
0.003		0.7346 ± 0.0003
0.004		0.8752 ± 0.0003
0.005		0.9895 ± 0.0003
0.006		1.0828 ± 0.0003
	30% Moisture Content	
0.001		0.3820 ± 0.0002
0.002		0.6447 ± 0.0003
0.003		0.8358 ± 0.0003
0.004		0.9811 ± 0.0004
0.005		1.0943 ± 0.0004
	10% Moisture Content	
0.001		0.5199 ± 0.0003
0.002		0.8253 ± 0.0004
0.003		1.0242 ± 0.0005
0.004		1.1627 ± 0.0005
0.005		1.2631 ± 0.0005

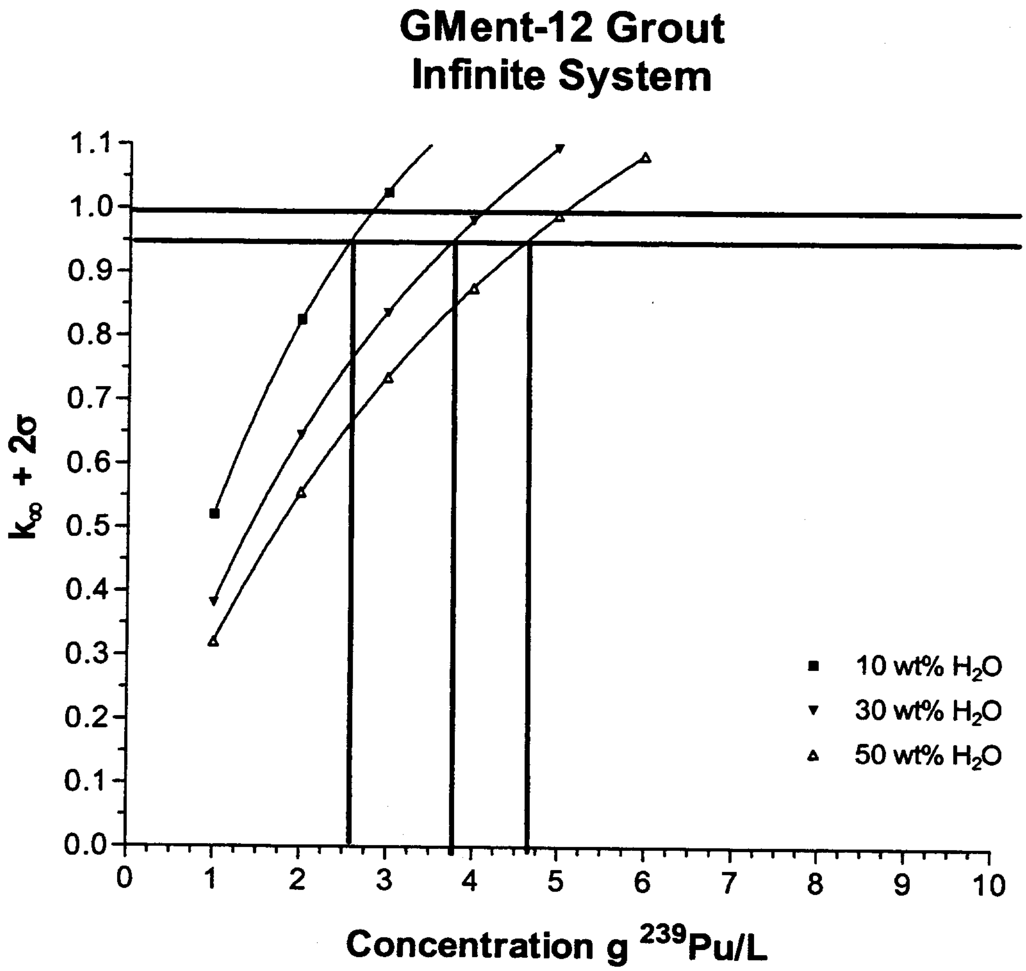

Figure C-7. Infinite GMENT-12 Study.

Table C-8. Finite (208 L) GMENT-12 Grout Parametric Study.

Pu Concentration in Grout (g/cc)	$k_{eff} \pm \sigma$
50% Moisture Content	
0.005	0.7321 ± 0.0007
0.006	0.8072 ± 0.0008
0.007	0.8709 ± 0.0008
0.008	0.9238 ± 0.0009
0.009	0.9698 ± 0.0009
0.010	1.0147 ± 0.0009
30% Moisture Content	
0.005	0.7018 ± 0.0009
0.006	0.7699 ± 0.0009
0.007	0.8227 ± 0.0010
0.008	0.8709 ± 0.0010
0.009	0.9131 ± 0.0011
0.010	0.9468 ± 0.0011
0.011	0.9702 ± 0.0011
0.012	1.0074 ± 0.0012
0.013	1.0262 ± 0.0012
10% Moisture Content	
0.010	0.6752 ± 0.0012
0.020	0.7953 ± 0.0013
0.030	0.8450 ± 0.0014
0.040	0.8700 ± 0.0015
0.050	0.8900 ± 0.0013
0.060	0.9039 ± 0.0014
0.070	0.9140 ± 0.0014
0.080	0.9236 ± 0.0014
0.090	0.9345 ± 0.0014
0.100	0.9411 ± 0.0014

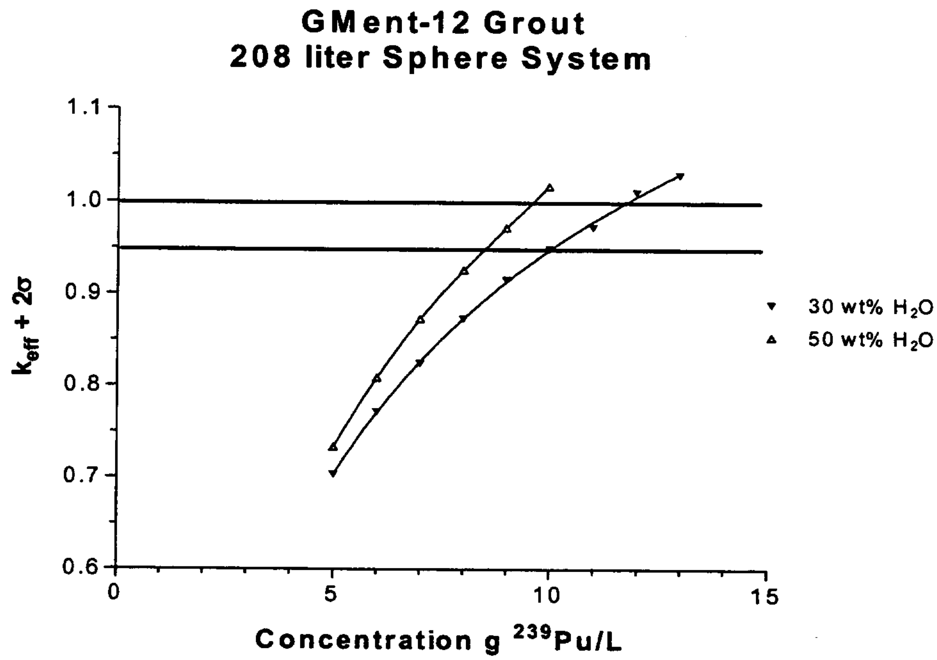

Figure C-8a. Finite (208 L) GMENT-12 Study—30 and 50% Water.

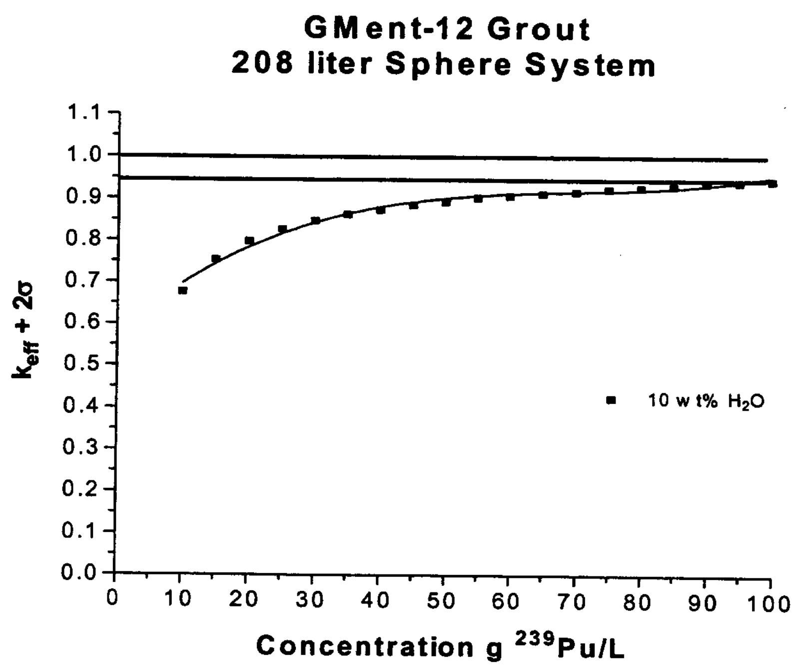

Figure C-8b. Finite (208 L) GMENT-12 Study—10% Water.

Table C-9. Infinite TECT HG Grout Parametric Study.

Pu Concentration in Grout (g/cc)		$k_\infty \pm \sigma$
	50% Moisture Content	
0.005		0.7769 ± 0.0003
0.006		0.8672 ± 0.0003
0.007		0.9456 ± 0.0004
0.008		1.0135 ± 0.0004
0.009		1.0739 ± 0.0004
	30% Moisture Content	
0.005		0.7410 ± 0.0004
0.006		0.8290 ± 0.0004
0.007		0.9065 ± 0.0004
0.008		0.9742 ± 0.0004
0.009		1.0346 ± 0.0004
0.010		1.0873 ± 0.0004
	10% Moisture Content	
0.005		0.7073 ± 0.0004
0.006		0.7931 ± 0.0004
0.007		0.8669 ± 0.0004
0.008		0.9314 ± 0.0005
0.009		0.9889 ± 0.0005
0.010		1.0398 ± 0.0005

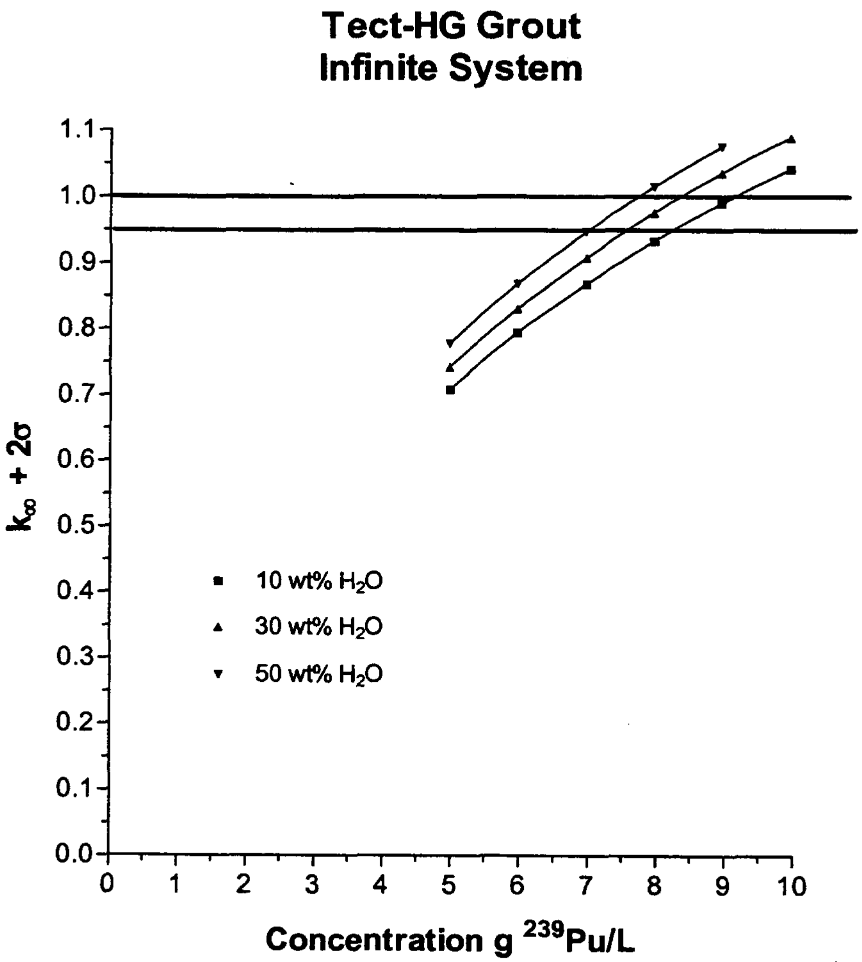

Figure C-9. Infinite TECT HG Study.

Table C-10. Finite (208 L) TECT HG Grout Parametric Study.

Pu Concentration in Grout (g/cc)	$k_{eff} \pm \sigma$
50% Moisture Content	
0.005	0.6155 ± 0.0005
0.010	0.9086 ± 0.0008
0.015	1.0757 ± 0.0010
0.020	1.1875 ± 0.0010
0.025	1.2603 ± 0.0011
30% Moisture Content	
0.005	0.5503 ± 0.0006
0.010	0.8221 ± 0.0008
0.015	0.9835 ± 0.0009
0.020	1.0846 ± 0.0010
0.025	1.1567 ± 0.0012
10% Moisture Content	
0.005	0.4112 ± 0.0006
0.010	0.6208 ± 0.0010
0.015	0.7474 ± 0.0010
0.020	0.8258 ± 0.0011
0.025	0.8827 ± 0.0012
0.030	0.9233 ± 0.0012
0.035	0.9558 ± 0.0013
0.040	0.9825 ± 0.0013
0.045	1.0003 ± 0.0013
0.050	1.0191 ± 0.0014
0.055	1.0285 ± 0.0013

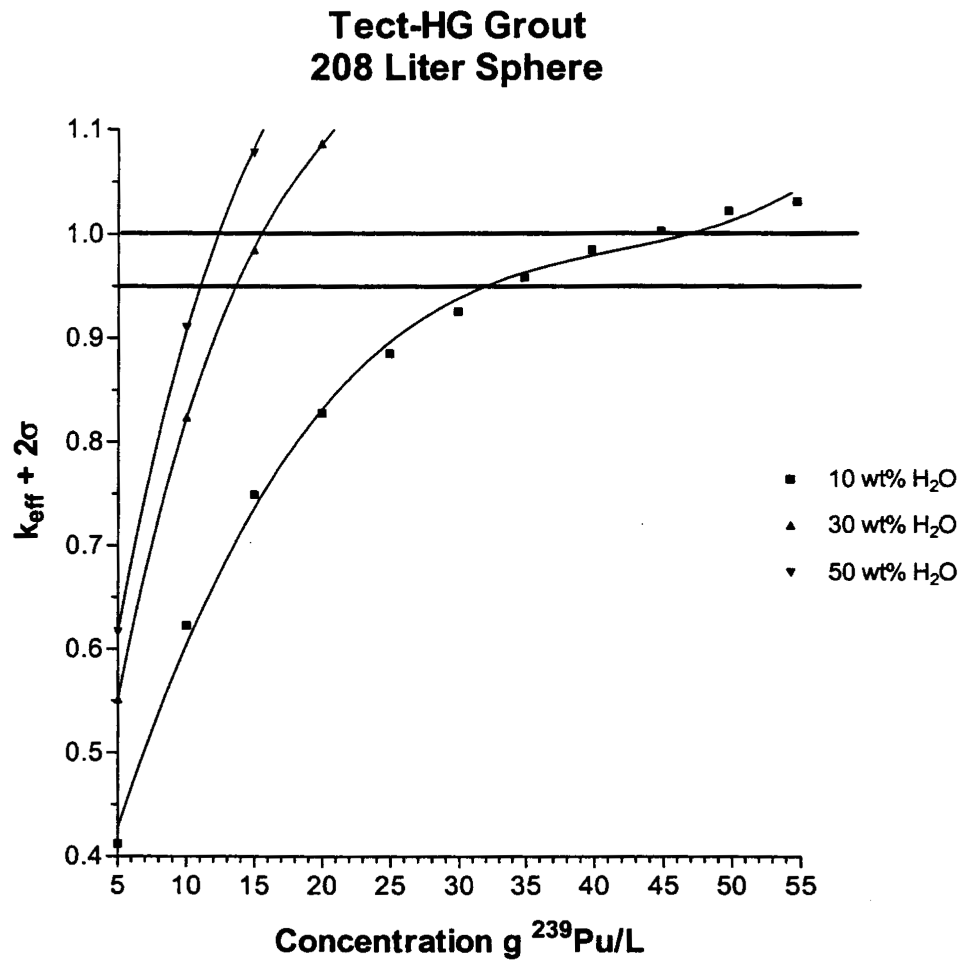

Figure C-10. Finite (208 L) TECT HG Study.

Table C-11. Infinite U.S. Grout Parametric Study.

Pu Concentration in Grout (g/cc)	$k_\infty \pm \sigma$
50% Moisture Content	
0.002	0.5096 ± 0.0002
0.003	0.6808 ± 0.0003
0.004	0.8178 ± 0.0003
0.005	0.9310 ± 0.0003
0.006	1.0240 ± 0.0003
30% Moisture Content	
0.001	0.3397 ± 0.0002
0.002	0.5837 ± 0.0003
0.003	0.7672 ± 0.0003
0.004	0.9103 ± 0.0003
0.005	1.0239 ± 0.0004
0.006	1.1163 ± 0.0004
10% Moisture Content	
0.001	0.4488 ± 0.0003
0.002	0.7356 ± 0.0004
0.003	0.9329 ± 0.0004
0.004	1.0749 ± 0.0004

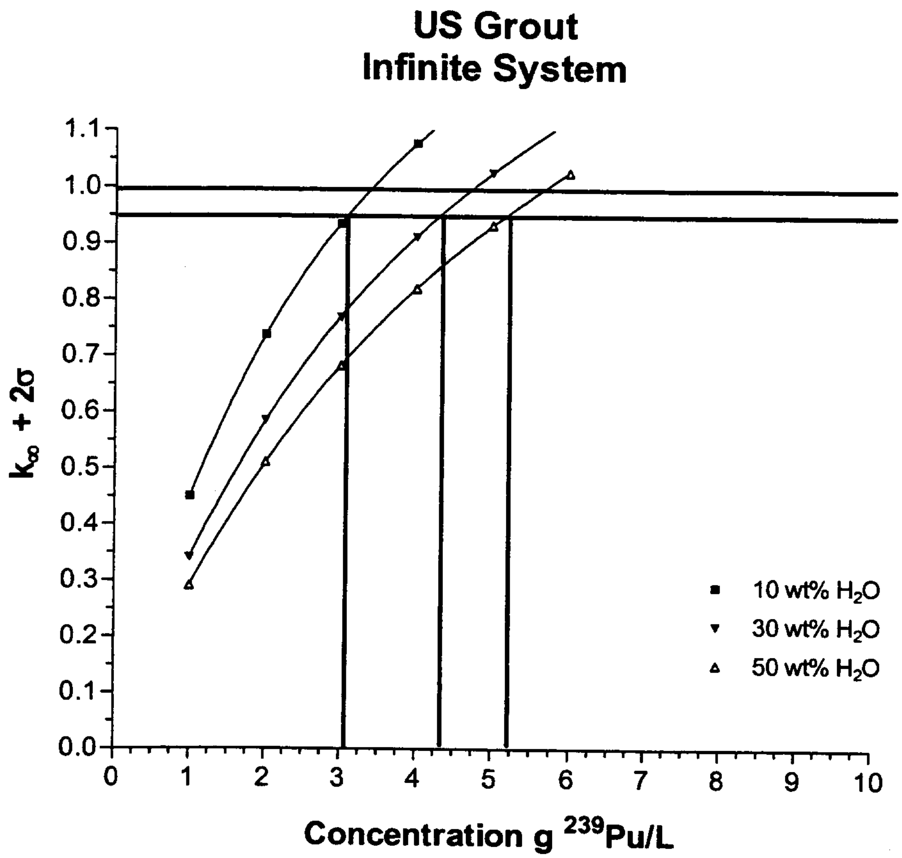

Figure C-11. Infinite U.S. Grout Study.

Table C-12. Finite (208 L) U.S. Grout Parametric Study.

Pu Concentration in Grout (g/cc)	$k_{eff} \pm \sigma$
50% Moisture Content	
0.003	0.5190 ± 0.0005
0.004	0.6294 ± 0.0006
0.005	0.7221 ± 0.0007
0.006	0.7964 ± 0.0008
0.007	0.8651 ± 0.0008
0.008	0.9228 ± 0.0008
0.009	0.9722 ± 0.0009
0.010	1.0152 ± 0.0009
30% Moisture Content	
0.005	0.7120 ± 0.0007
0.006	0.7947 ± 0.0009
0.007	0.8568 ± 0.0009
0.008	0.9055 ± 0.0009
0.009	0.9544 ± 0.0010
0.010	0.9892 ± 0.0010
0.011	1.0270 ± 0.0010
0.012	1.0568 ± 0.0011
10% Moisture Content	
0.010	0.8097 ± 0.0012
0.020	0.9589 ± 0.0014
0.030	1.0175 ± 0.0014
0.040	1.0465 ± 0.0014
0.050	1.0677 ± 0.0014

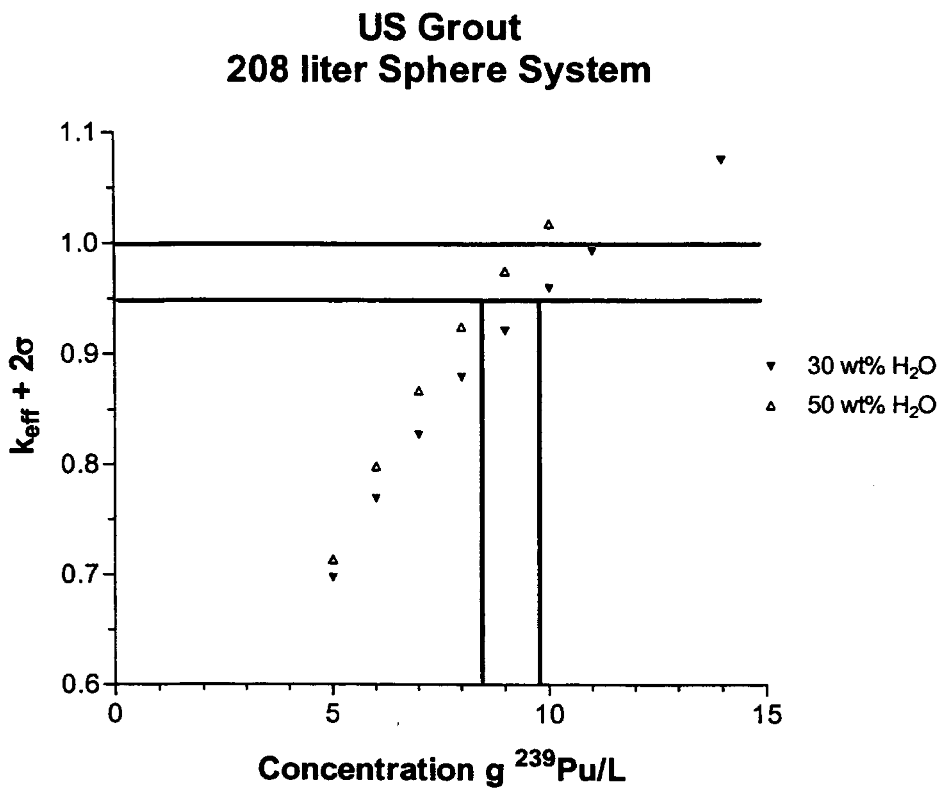

Figure C-12a. Finite (208 L) U.S. Grout Study—30 and 50 wt% H_2O.

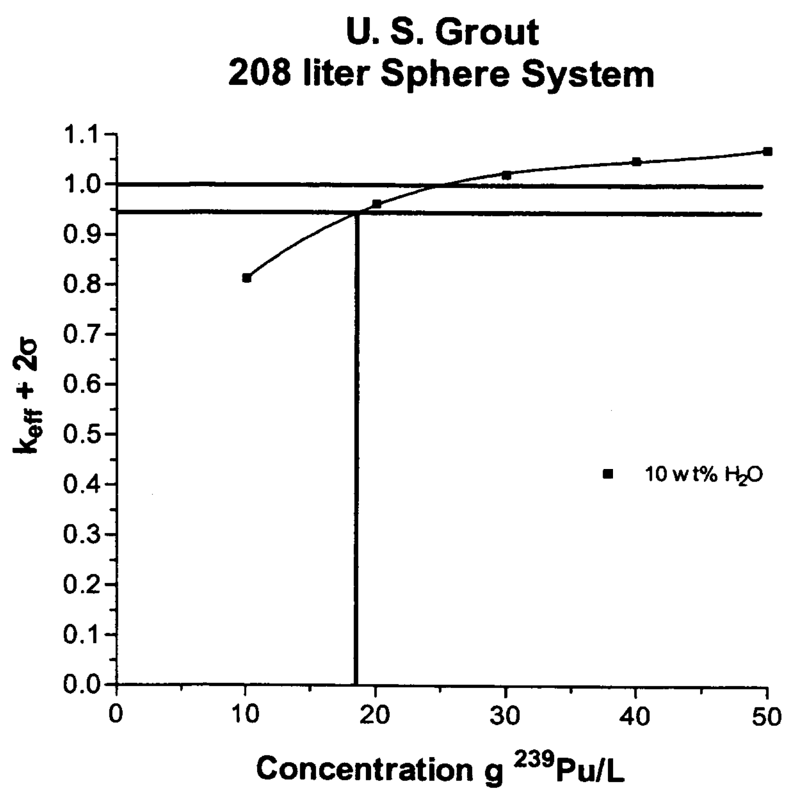

Figure C-12b. Finite (208 L) U.S. Grout Study—10 wt% H_2O.